MULTI-OBJECTIVE OPTIMIZATION MODEL FOR WATER RESOURCES MANAGEMENT IN SAUDI ARABIA

BY

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Dedication

To my beloved parents, brothers and sisters, for their endless love and support

ACKNOWLEDGMENTS

I would like to use this space to firstly thank the Almighty Allah for giving me knowledge, effort and patience to end up with this work. I feel the need to say thanks to King Fahd University of Petroleum and Minerals (KFUPM), representative by the Department of Civil and Environmental Engineering, Dhahran, Saudi Arabia, for providing me an opportunity to successfully complete my M.Sc. in Water Resources and Environmental Engineering. My sincere thanks extend to my thesis advisor, Dr. Md. Shakhawat Hossain Chowdhury for his ongoing guidance and cooperation during my work on this thesis, the space is not enough to evaluate his tremendous efforts that made this task possible, by Allah's will. I am also thankful to my thesis committee members, Dr. Muhammad Abdallah Al-Zahrani for his valuable suggestions in completion of my thesis, Dr. Mohammad Saleh Al-Suwaiyan for his assistance and support during this work. Acknowledgement is due to the Chairman of the Department of Civil and Environmental Engineering, all staff and faculty members for providing the facilities to complete my study. Many thanks goes to my classmates in KFUPM for filling the days with friendships and laughter. Warmest thanks to my roommate Mr. Ibrahim Abdelkareem Mohammed, M.Sc. student in Medical Physics, for his honest brotherhood and wonderful moments we spent together throughout our study in KFUPM. Special thanks to my friends, colleagues and all the good people, far and near, who have encouraged me during my work in this research. I owe my deepest gratitude to my family members for their prayers, encouragement and endless support.

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LIST OF ABBREVIATIONS

BCM	Billion Cubic Meter
DW	Desalinated Water
FAO	Food and Agriculture Organization
GP	Goal Programming
GW	Groundwater
GWW	Generated Wastewater
LPCD	Liter per Capita per Day
MAW	Ministry of Agriculture and Water
MCM	Million Cubic Meter
MFNE	Ministry of Finance and National Economy
MODM	Multi-objective decision making
MOEP	Ministry of Economy and Planning
MOP	Ministry of Planning
MOW	Ministry of Water
MOWE	Ministry of Water and electricity
ppm	Part Per Million

RO	Reverse Osmosis
SGS	Saudi Geology Survey
SR	Saudi Riyal
SSYB	Saudi Statistical Year Book
SW	Surface Water
SWCC	Saline Water Conservation Corporation
TDS	Total Dissolved Solids
TWW	Treated Wastewater
WBS	Water Blending Stations
WMO	World Meteorological Organization

LIST OF NOTATIONS

R_i	Indicates to the *i*th priority;
W_i	Assigned weight given to indicate the importance of the *i*th priority;
i	Index for a priority rank (i = 1, 2, 3… 11);
Q^{GW}	The current extraction of GW (MCM/year);
Q^{SW}	The current capacity of dams constructed for drinking and irrigation purposes (MCM/year);
Q^{DW}	The current supply of DW (MCM/year);
Q^{TWW}	The predicted generation of domestic wastewater (MCM/year);
Q^{D}	Domestic water demand (MCM/year);
Q^{A}	Agricultural water demand (MCM/year);
Q^{I}	Industrial water demand (MCM/year);
TDS^{GW}	TDS of GW (ppm);
TDS^{SW}	TDS of SW (ppm);
TDS^{DW}	TDS of DW (ppm);
TDS^{TWW}	TDS of TWW (ppm);
TDS^{D}	Required TDS of domestic water (ppm);
TDS^{A}	Required TDS of agricultural water (ppm);
TDS^{I}	Required TDS of industrial water (ppm);

C^{GW}	Unit cost of using GW (SR/m^3);
C^{SW}	Unit cost of using SW (SR/m^3);
C^{DW}	Unit cost of using DW (SR/m^3);
C^{TWW}	Unit cost of reusing TWW (SR/m^3);
q_D^{GW}	GW supplied to domestic sector (MCM/year);
q_A^{GW}	GW supplied to agricultural sector (MCM/year);
q_I^{GW}	GW supplied to industrial sector (MCM/year);
q_D^{SW}	SW supplied to domestic sector (MCM/year);
q_A^{SW}	SW supplied to agricultural sector (MCM/year);
q_D^{DW}	DW supplied to domestic sector (MCM/year);
q_A^{TWW}	TWW reused in agricultural sector (MCM/year);
P^{GW}	Positive deviation above the current extraction of GW (MCM/year);
N^{GW}	Negative deviation below the current extraction of GW (MCM/year);
P^{SW}	Positive deviation above the current capacity of dams constructed for drinking and irrigation purposes (MCM/year);
N^{SW}	Negative deviation below the current capacity of dams constructed for drinking and irrigation purposes (MCM/year);
P^{DW}	Positive deviation above the current supply of DW (MCM/year);
N^{DW}	Negative deviation below the current supply of DW (MCM/year);

P^{TWW} Positive deviation above the predicted generation of domestic wastewater (MCM/year);

N^{TWW} Negative deviation below the predicted generation of domestic wastewater (MCM/year);

P_D Positive deviation above the domestic water demand (MCM/year);

N_D Negative deviation below the domestic water demand (MCM/year);

P_A Positive deviation above the agricultural water demand (MCM/year);

N_A Negative deviation below the agricultural water demand (MCM/year);

P_I Positive deviation above the industrial water demand (MCM/year);

N_I Negative deviation below the industrial water demand (MCM/year);

$P_{D(blend)}^{TDS}$ Positive deviation of the quality of blended GW with DW above the required quality of domestic water (ppm);

$N_{D(blend)}^{TDS}$ Negative deviation of the quality of blended GW with DW below the required quality of domestic water (ppm);

$P_{D(GW)}^{TDS}$ Positive deviation of GW quality above the required quality of domestic water (ppm);

$N_{D(GW)}^{TDS}$ Negative deviation of GW quality below the required quality of domestic water (ppm);

$P_{D(SW)}^{TDS}$ Positive deviation of SW quality above the required quality of domestic water (ppm);

$N_{D(SW)}^{TDS}$ Negative deviation of SW quality below the required quality of domestic water (ppm);

$P_{A(GW)}^{TDS}$ Positive deviation of GW quality above the required quality of agricultural water (ppm);

$N_{A\,(GW)}^{TDS}$ Negative deviation of GW quality below the required quality of agricultural water (ppm);

$P_{A\,(SW)}^{TDS}$ Positive deviation of SW quality above the required quality of agricultural water (ppm);

$N_{A\,(SW)}^{TDS}$ Negative deviation of SW quality below the required quality of agricultural water (ppm);

$P_{A\,(TWW)}^{TDS}$ Positive deviation of TWW quality above the required quality of agricultural water (ppm);

$N_{A\,(TWW)}^{TDS}$ Negative deviation of TWW quality below the required quality of agricultural water (ppm);

$P_{I\,(GW)}^{TDS}$ Positive deviation of GW quality above the required quality of industrial water (ppm);

$N_{I\,(GW)}^{TDS}$ Negative deviation of GW quality below the required quality of industrial water (ppm);

P_{GW}^{C} Positive deviation above the cost of using the current extraction rate of GW (million SR /year);

N_{GW}^{C} Negative deviation below the cost of using the current extraction rate of GW (million SR /year);

P_{SW}^{C} Positive deviation above the cost of using SW with the quantity equals to the current capacity of dams constructed for drinking and irrigation purposes (million SR /year);

N_{SW}^{C} Negative deviation below the cost of using SW with the quantity equals to the current capacity of dams constructed for drinking and irrigation purposes (million SR /year);

P_{DW}^{C} Positive deviation above the cost of using the current supply rate of DW (million SR /year);

N_{DW}^{C} Negative deviation below the cost of using the current supply rate of DW (million SR /year);

P_{TWW}^{C} Positive deviation above the cost of reusing the predicted generation rate of domestic wastewater (million SR /year);

N_{TWW}^{C} Negative deviation below the cost of reusing the predicted generation rate of domestic wastewater (million SR /year)

THESIS ABSTRACT (ENGLISH)

Full Name: **Ammar Ahmed Mohammed Musa**

Thesis Title: **Multi-Objective Optimization Model for Water Resources Management in Saudi Arabia**

Major Field: **Civil and Environmental Engineering (Water Resources and Environmental Engineering)**

Date of Degree: **December, 2014**

This research developed a multi-objective model for reasonable distributions of water from multiple sources to multiple users from 2015 through 2050 in Saudi Arabia. The goal programming (GP) technique was used for model development. The supply sources are groundwater (GW), surface water (SW), desalinated water (DW) and treated wastewater (TWW), while the users are domestic, agricultural and industrial sectors. The model was applied to: (i) satisfy water demands and water quality; (ii) maximize TWW reuse, SW supply and GW conservation; and (iii) minimize DW overproduction and overall cost. Uncertainties in water demands and supplies were incorporated through generating 100 random realizations of water demands and supplies. The model identified the combinations of source wise supplies for satisfying sector wise demands from 2015 to 2050. Distributions of GW and SW in domestic sectors are estimated to be 458.1 and 207.7 MCM, respectively in 2015, which are predicted to be 585.3 and 349.1 MCM, respectively in 2050. In 2015 and 2050, DW supplies are 1959.4 and 4494.8 MCM, respectively. Supply of GW and SW for agriculture may be reduced from 10483 and

236.6 to 8753 and 95.2 MCM from 2015 to 2050, respectively, which is compensated by maximizing TWW reuse. GW supply to industrial sectors may increase from 992.6 MCM in 2015 to 6428.3 MCM in 2050. In 2015, the predicted supplies of GW, DW and TWW are 11933.4, 1959.3 and 2074.4 MCM, respectively, which are projected to be 15766.4, 4494.8 and 3945.8 MCM, respectively in 2050. The predicted supply of SW is 444.3 MCM/year. GW source is likely to satisfy the predicted quantities till 2035, thereafter, probabilities of satisfying the predicted quantities show decreasing trend. Supply of DW and TWW needs to be increased to satisfy the predicted quantities during 2015-2050. The cost for using water from different sources in 2015 is estimated to be 47.4 billion SR, which is predicted to be 82 billion SR in 2050.

DEGREE OF MASTER OF SCIENCE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

DHAHRAN, SAUDI ARABIA

THESIS ABSTRACT (ARABIC)

الإســـم الكامل: **عمار أحمد محمد موسى**

عنوان الرسالة: **نموذج أمثل متعدد الأغراض لإدارة موارد المياه في المملكة العربية السعودية**

التـــخصـــص: **الهندسة المدنية والبيئية (هندسة الموارد المائية و البيئية)**

تاريـخ الـدرجـة العلمية: **ديسمبر، 2014 م**

في هذا البحث تم تطوير نموذج متعدد الأغراض يهدف إلى المساهمة في توزيع المياه من مصادر متعددة إلي العديد من الإستخدامات وذلك للفترة من عام 2015 حتي 2050 في المملكة العربية السعودية. وقد تم إستخدام تقنية تسمي برمجمة الهدف لتطوير النموذج. إن مصادر المياه المتوفرة في المملكة هي: المياه الجوفية، المياه السطحية، المياه المحلاة ومياه الصرف الصحي المعالجة، بينما المستخدمين هم: القطاعات المنزلية، الزراعية والصناعية. تم تطوير النموذج آخذاً في الإعتبار كل من الأهداف التالية: (1) تحقيق طلبات و جودة المياه في قطاعات الإستهلاك المختلفة، (2) رفع معدل إعادة إستخدام مياه الصرف الصحي المعالجة، الإستفادة القصوى من المياه السطحية، و الحفاظ علي المياه الجوفية، و(3) تقليل كمية المياه المحلاة المنتجة وكذلك تقليل كلفة إنتاج المياه من مصادر مختلفة. وقد وضع في الحُسبان الشكوك وعدم الدقة التي ربما تصاحب تنبؤات إمدادات و طلبات المياه، و ذلك عن طريق توليد 100 رقم عشوائي بناءً علي البيانات المتوقعة. كما حدد النموذج العلاقة بين إمدادات المياه من مصادر مختلفة لتحقيق طلبات المياه في قطاعات الإستهلاك المختلفة للفترة من 2015 حتى 2050. ويقدر إستهلاك المياه الجوفية والسطحية في القطاعات المنزلية بحولي 458.1 و207.7 مليون متر مكعب، علي التولي في عام 2015، ومن المتوقع أن تكون حوالي 585.3 و349.1 مليون متر مكعب، على التوالي بحلول العام 2050. و في عامي

2015 و2050، يقدر إمداد المياه المحلاة في القطاعات المنزلية بحوالي 1959.4 و 4494.8 مليون متر مكعب، على التوالي. من المرجح أن يُخفض إستهلاك المياه الجوفية و السطحية في الزراعة من 10483 و236.6 مليون متر مكعب إلى 8753 و 95.2 مليون متر مكعب في الفترة من 2015 إلى 2050، علي التوالي، بينما يُعوض هذا الإنخفاض بزيادة إعادة إستخدام مياه الصرف الصحي المعالجة. و أوضحت النتائج بأن إمداد المياه الجوفية في القطاعات الصناعية يزيد من 992.5 مليون متر مكعب في العام 2015 إلى 6428.3 مليون متر مكعب بحلول العام 2050. كما أن الكميات المتوقع إمدادها من مصادر المياه الجوفية، المياه المحلاة و مياه الصرف الصحي المعالجة في العام 2015 تقدر بحوالي 11933.4، 1959.3 و2074.4 مليون متر مكعب، علي التوالي، و من المحتمل أن تكون 15766.4، 4494.8 و3945.8 مليون متر مكعب، علي التوالي في عام 2050. كما توصلت الدراسة إلى أن إمدادات المياه السطحية المتوقعة خلال هذه الفترة تقدر بحوالي 444.3 مليون متر مكعب في السنة. ومن المحتمل أن تُلبي الإمدادت الحالية لمصادر المياه الجوفية الكميات المتوقعة حتى عام 2035، بعدئذ، فإن إمكانية توفير هذه الكميات من الإمدادات الحالية قد تتناقص. و خلصت الدراسة إلى أن الإمدادات الحالية لمياه التحلية والمياه العادمة المعالجة لا تكفي لتلبية الكميات المتوقعة خلال الفترة من 2015– 2050، لذا لابد من زيادة الإمدادات الحالية من هذه المصادر. كما إستنتجت الدراسة إلى أن تكلفة إمدادات المياه من المصادر المختلفة في عام 2015 تبلغ حوالي 47.4 مليار ريال سعودي، و قد تبلغ 82 مليار ريال سعودي بحلول عام 2050.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 Background

Water is an essential component of all ecosystems and a basic element of life. The Earth contains approximately 1.386 billion km^3 of water, with 97.5% and 2.5% of saline and fresh water respectively. Approximately two-thirds of this fresh water is stored in glaciers, which cannot be utilized. The remaining 0.8% is available in aquifers, rivers, lakes and storage reservoirs, while only 0.3% of the total freshwater is available in liquid form on the surface [1]. The available world water resources have become under increasing stress due to population increase, increased urbanization and industrialization, expansion of agricultural activities, water quality deterioration and global climate changes [2].

Understanding of water resources and water consumptions is vital to develop sustainable water resources management strategy [3]. Many countries including Australia, China, India and Spain are observing dramatic increase in water demands, which have already started exceeding supply resulting in water stress. The issue appears to be serious in the Middle East, where water resources are limited and vulnerable [4].

Saudi Arabia is a water deficit country, where optimization of water resources plays a significant role [5]. The water consumption patterns and resources indicate that Saudi

Arabia needs to manage water resources more efficiently. The difficulty associated with water resources management is to provide a balance between water demands and available water resources. To achieve sustainability in water resources, effective management of water resources needs to be followed. Optimal allocations of water supplies from different resources are necessary to satisfy water demands in various sectors. In this research, optimal allocations from different sources and the related issues were addressed. This chapter demonstrates the general features of the study region.

1.2 Study Region

Saudi Arabia is situated in an arid region, with an area of about 2.2 million square kilometers and is the largest country in the Arabian Peninsula (Figure 1.1) [5]. The country experiences relatively harsh climate, characterized by low annual rainfall and high evapotranspiration [5, 6]. The average annual rainfall is approximately 125 mm [5]. Chowdhury and Zahrani [6] predicted the average reference evapotranspiration in the range of 0.245 - 0.368 m/year for 2011-2050 , whereas the increase of temperature was projected to be 1.8 – 4.1°C during this period. The country is divided into thirteen administrative regions: Riyadh, Makkah, Madinah, Qaseem, Eastern region, Aseer, Hail, Tabouk, Al-Baha, Northern borders, Al-Jouf, Jazan, and Najran [7]. The locations, areas and populations of these regions are shown in Figures 1.1, 1.2 and 1.3, respectively, whereas the summary of climatic conditions is presented in Table 1.1.

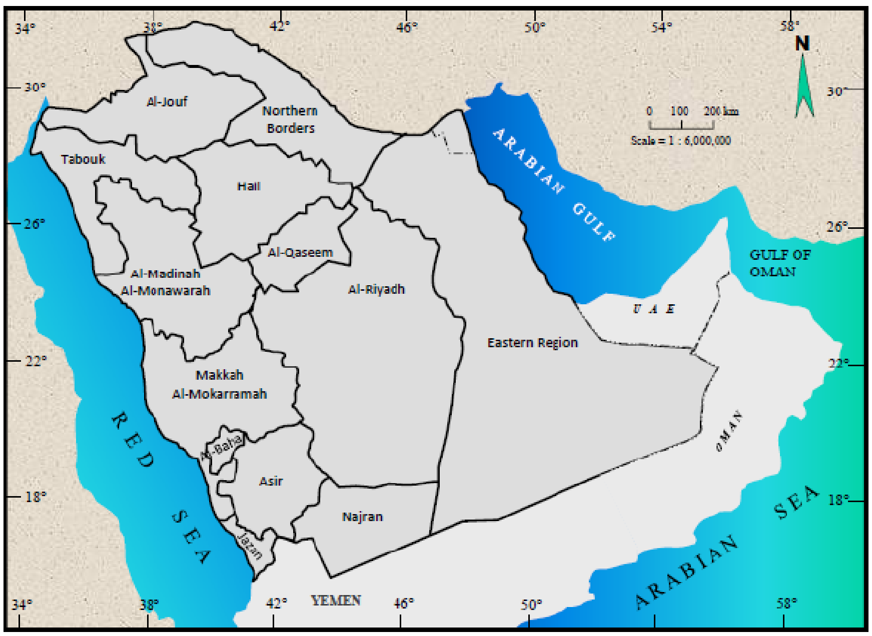


Figure 1.1: Map of Saudi Arabia and locations of the regions under consideration [3].

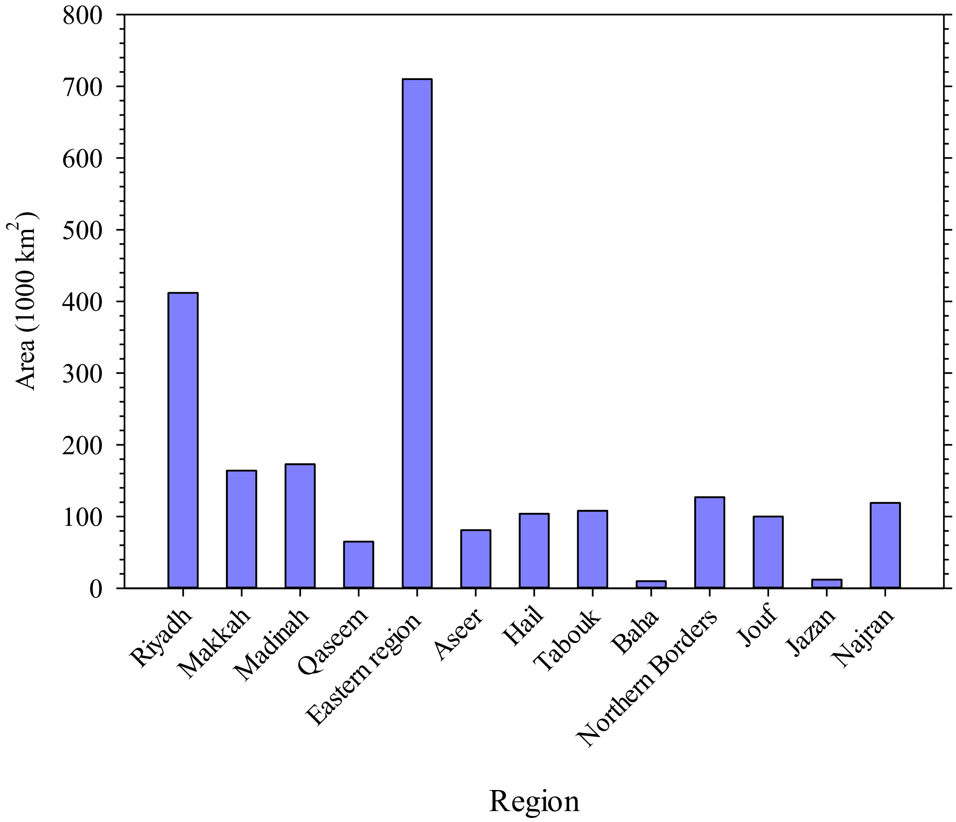


Figure 1.2: Areas of different regions in Saudi Arabia [8].

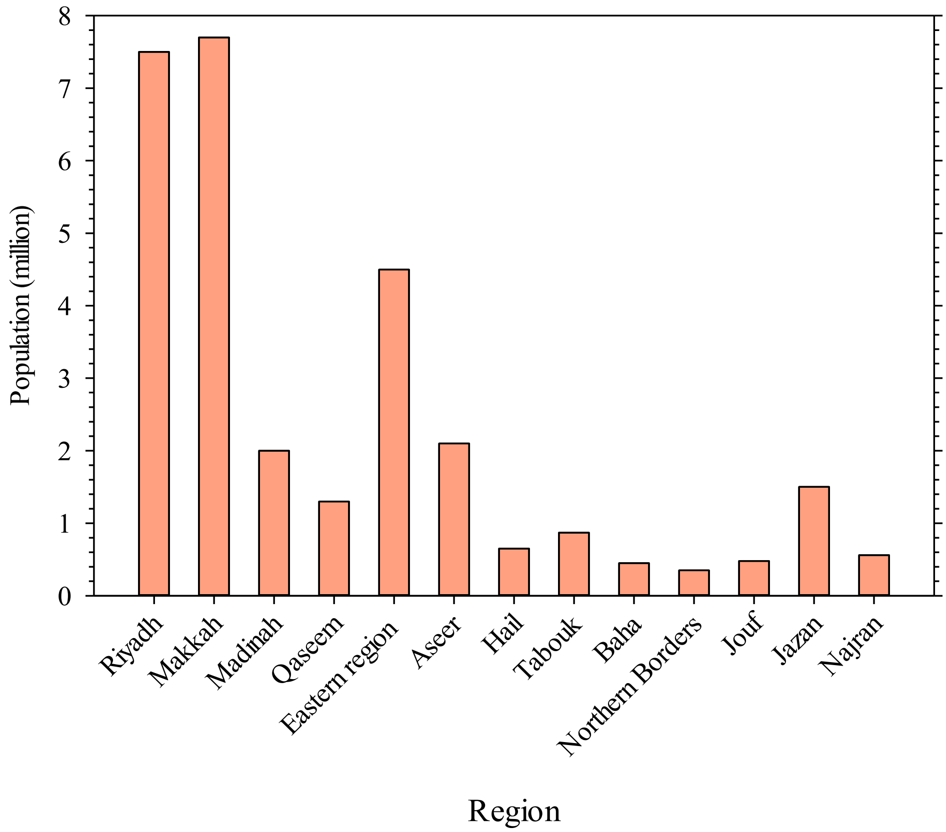


Figure 1.3: Population in 2013 for different regions in Saudi Arabia [9].

Table 1.1-1: Summary of climatic conditions in different regions of Saudi Arabia [7, 8].

Region	Temperature (°C)	Annual rainfall (mm)	Annual evapotranspiration (mm)	Relative humidity (%)	Wind speed (km/hr)	Sunshine period (hr)
Riyadh	8.2 - 42.8	101.3	1168 - 3978.5	15 - 51	6.5 - 13.9	6.3 - 9.6
Makkah	18.9 - 37.6	59	1628 - 2763	61 - 69	9 - 18	6.2 - 9.8
Madinah	11.6 - 42.2	49.1	1259 - 3500	14 - 43	7.4 - 13	5.4 -10.3
Qaseem	6.5 - 41.4	183	1037 - 3508	13 - 52	7.2 - 12.6	5.4 -10.3
Eastern Region	9.2 - 41.2	166	803 - 3174	32 - 65	6.8 - 10	6 - 9.2
Aseer	7.5 - 30.5	265	1102 - 2413	30 - 82	7.2 - 18	6.4 - 9
Hail	3.4 - 37.6	171	938 - 3281	17 - 57	9 – 12.6	6.1 - 10.8
Tabouk	3.0 - 37.8	28	898 - 3124	21 - 50	7.2 – 12.6	4.8 - 10.2
Al-Baha	8.9 - 37.9	124	1296 - 2796	18 - 47	7.2 - 10.8	6.3 - 8.9
Northern Borders	NA	NA	NA	NA	NA	NA
Al-Jouf	3.5 - 38.5	58	934 - 3979	13 - 58	10.8 - 16.2	6.1 - 10.9
Jazan	22.1 - 37.5	104	1570 - 2672	61 - 72	10.8 - 16.2	7.1 - 8.9
Najran	8.4 - 38.5	136	1475 - 3128	13 - 38	5.4 - 10.8	6.4 - 8.7

NA: Not available.

Since 1975, Saudi Arabia has rapid development coupled with population growth and living standards [10-12]. During 1972 to 2013, the population in Saudi Arabia has increased from 6.9 million to 30 million [9]. The rapid increase in population has resulted in significant increase in water use in the country [13]. The total water consumptions in the country were reported to be approximately 27000, 31500, 18500, 20500, 20200 and 18500 million cubic meter (MCM) in 1990, 1992, 1997, 2000, 2004 and 2009 respectively [14-16]. It can be noted that, in 1990 and 1992, agricultural sector witnessed high water demands due to extensive agricultural activities during these years [16]. The Ministry of Economy and Planning (MOEP) reported a decline of agricultural water demands by 2.5% per year between 2004 and 2009, which was achieved by reducing agricultural production and/or introducing advanced irrigation technique [7, 16]. The country is also planning to reduce agricultural water demands by 3.7% per year from 2009 to 2014 [16]. In contrast, domestic and industrial water demands are expected to increase by 2.1% and 5.5% per year, respectively, between 2009 and 2014 [16]. Water demands in the country are satisfied by groundwater (GW), surface water (SW), desalinated water (DW) and treated wastewater (TWW), while the GW supplies the most [16, 17].

GW resources in Saudi Arabia exist in two main sources: non-renewable or fossil GW in deep rock aquifers, located mostly in the Arabian Shelf, extending over thousands of square kilometers with poor natural recharge. The renewable GW is available in the shallow alluvial aquifers, located mostly in the western and southwestern parts of the country [10]. In 1984, the proven, probable and possible non-renewable GW reverses was reported to be 259.1, 415.6 and 760.6 billion cubic meters (BCM), respectively, while significant fraction of this water might have been consumed in the past years [18-20]. The total internal renewable GW was estimated to be 2.4 BCM/year [5]. There is no natural surface water flow in the country. Surface runoff occurs mainly in the form of intermittent flash floods, which is governed by rainfalls and topographic features over the country [21, 22]. To facilitate storage and recharge of surface runoff, a total of 394 dams across the country store approximately 1.9 BCM per year of surface runoff [22]. The seawater desalination plants in the country satisfy more than 50% of the total domestic demands, producing approximately 1476 MCM of DW in 2011, while the domestic water demand in 2011 was 2428 MCM [22, 23]. A total of 81 wastewater treatment plants treated approximately 730 MCM of domestic wastewater in 2008, while their current capacity is approximately 1729 MCM/year [16, 22]. However, only 325 MCM of TWW was recycled for reuse in 2009. The TWW was mostly used for agricultural, landscaping and industrial purposes [16].

1.3 Problem Definition and Justifications

Scarcity of water has become an issue in Saudi Arabia, which has made it hard for the country to keep pace with water demands. The Saudi government has been spending substantial amount of revenues to construct new water supply sources and to expand the older facilities [23]. The water reserves and withdrawal rates denote that the available resources may not be sufficient to supply water on a long-term basis [6, 18-20], whereas there is a potential to fully reuse domestic wastewater. The GW in Saudi Arabia is an invaluable resource and its rapid depletion may have environmental and socioeconomic impacts. Alternative sources of water supplies, such as TWW reuse for industrial and agricultural purposes, construction of new dams to augment surface water runoff collection, etc. are needed to satisfy water demands.

This study addresses the issues related to maximizing conservation of GW and ensuring sustainable water supplies to all consumers by allocating optimal amount of water from the limited available resources. This research aimed at formulating water resources management model through optimizing multiple objectives related to different sources and demands (such as, water quantity, quality and cost).

In this study, multiple objectives, such as, multiple resources, multiple consumers, water quality satisfaction for multiple consumers and cost optimization for these consumers, were involved. As such, multiple constraints were also present. The multiple objective decision making technique is the appropriate approach to deal with such problem. Therefore, the multi-objective optimization technique has been adopted in this study.

1.4 Objectives of the Research

The main objective of the research was to develop and apply a multi-objective model for optimal distribution of water supplies from different resources to domestic, agricultural and industrial sectors in Saudi Arabia. The main objective was achieved through considering the following aspirations:

i. Satisfy domestic, agricultural and industrial water demands from 2015 through 2050 in different regions of Saudi Arabia.
ii. Control water quality for domestic, agricultural and industrial uses.
iii. Maximize TWW reuse in the agricultural sector.
iv. Maximize SW use.
v. Minimize GW extraction.
vi. Minimize DW overproduction.
vii. Minimize overall cost of water consumption for the domestic, industrial and agricultural sectors.

1.5 Thesis Organization

This thesis was organized in a total of six chapters. The content of each chapter is explained below:

Chapter 1: This chapter includes of the background of the work and a brief description of the study region. The importance and justifications for this research are explained. The objectives of the research are presented.

Chapter 2: In this chapter, a detailed literature review is presented where focus was given to water resources management. This chapter presents an overview concerning characteristics of water resources, trends of water consumptions and costs of supplying water from different sources in Saudi Arabia. The theories and techniques related to multi-objective optimization models are summarized.

Chapter 3: This chapter presents the methodology. The reasons for selecting goal programming approach are stated. The development of goal programming model is explained. Lastly, description and procedures of using the LINGO optimizer software to solve the model are illustrated.

Chapter 4: Chapter four presents the data generation, sources and analysis.

Chapter 5: In this chapter, summary and discussions on the results are presented.

Chapter 6: This chapter has been dedicated to the conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Water resources management can be defined as optimal allocation of water from existing resources to various sub-sectors as per permits or licenses [24]. It is an approach to accomplish appropriate utilization of water in competing and conflicting demands [25]. It relies on participatory program, involving planners, users, engineers, financial specialists, environmentalists and policy-makers [26]. The integrated management of water resources may result in several positive consequences including water conservation and comprehensive consensus to allocate reasonable amounts of water to different sectors [27].

Saudi Arabia is facing scarcity in water resources. To satisfy the sector-wise water consumptions, substantial amount revenues has been being spent to construct new water supply sources and to expand the older facilities [23]. During 1985 through 1990, the Saudi government had allocated approximately 30 billion Saudi Riyal (SR) for water supply projects; in which 66% was spent for constructing new desalination plants and for operating and maintaining the current ones [22]. The sixth development plan of the MOEP reported that the total budget allocated to water sector in Saudi Arabia in the period 1990 – 1995 was 40 billion SR, from which 16.8 billion was allocated for desalinated water production [23]. Past studies have shown relatively higher rates of GW withdrawal, which may result in the rapid depletion of GW level and degradation of water quality. GW is an invaluable resource in Saudi Arabia and its fast depletion may have harmful socioeconomic and environmental implications [6, 18]. Alternative source of water such as, constructing new desalination plants and maximize reclaimed wastewater for agricultural purposes, are required to satisfy the increasing water demands.

2.2 Characteristics of Water Resources in Saudi Arabia

2.2.1 Groundwater

Geologically, Saudi Arabia is divided into the Arabian Shield and the Arabian Shelf. The Arabian Shield constitutes one-third of the Arabian Peninsula, comprise of an outcrop of hard rock, which starts in the western portion of Saudi Arabia and stretches from the Gulf of Aqaba in the north to the Gulf of Aden in the south. The Shield has finite GW reserves in the alluvial deposits to wadi channels, weathered joints and fracture zones. The Arabian Shelf is predominantly composed of limestone and sandstone, which overlies the Arabian Shield and covers two-third of the Arabian Peninsula [10, 28]. GW resources in Saudi Arabia are divided into two types: non-renewable or fossil GW in deep rock aquifers and renewable GW in the shallow alluvial aquifers.

2.2.1.1 Non-renewable Groundwater

GW is stored in the deep rock and sedimentary aquifers, extending over thousands of square kilometers with poor natural recharge [18, 29]. The GW in the deep aquifers is non-renewable (fossil water), which was composed about 10 to 32 thousand years ago, and is confined in limestone and sandstone formations with a thickness of 300 m at a depth of 150 – 500 m [28]. The principle aquifers for non-renewable water are: Saq, Wajid, Tabouk, Minjur, Dhurma, Biyadh, Wasia, Dammam, Umm Er Radhuma and Neogene [18, 29]. The approximate locations of these aquifers are shown in Figure 2.1.

Variable quantities of non-renewable GW in Saudi Arabia have been reported. The Ministry of Planning reported that the GW reserves were 338 BCM with 500 BCM of probable reserves [5]. Past studies have indicated that the proven, probable and possible reserves of GW were 353.2, 405 and 705 BCM, respectively [5]. The natural annual recharge to these aquifers was estimated to be 1.28 BCM [29], in which nearly 395 MCM/year is drained out from Saudi Arabia. It is likely that significant fraction of this water might have been used in the past [18-20]. Some aquifers revealed remarkable declines in water level. For instance, the piezometric level in Minjur aquifer dropped from 45 to 75 meter beneath ground surface over the period of 1965 – 1980 [30]. Similarly, a decline in water level took place for the Wasia aquifer [28]. In addition, during 1965 – 1975 and 1979 – 1981 Saq aquifer was reduced by 15 m in the east of Buraydah city and by 5 meter near the middle of Buraydah city, respectively [28]. Abderrahman [14, 15] reported that GW withdrawals in 1990, 1992 and 1997 were 24.5, 28.6 and 15.4 BCM, respectively. The Ninth Development Plan of MOEP indicated that the extraction rates from the non-renewable GW sources in 2004 and 2009 were 13.5 and 11.6 BCM, respectively [16]. In 2014, this withdrawal is forecasted to be approximately 9.0 BCM [16]. The reduction in GW extraction is due to the reduction of agricultural water demands [16]. At this level, the GW sources are subjected incessant stress and may not survive for a long term.

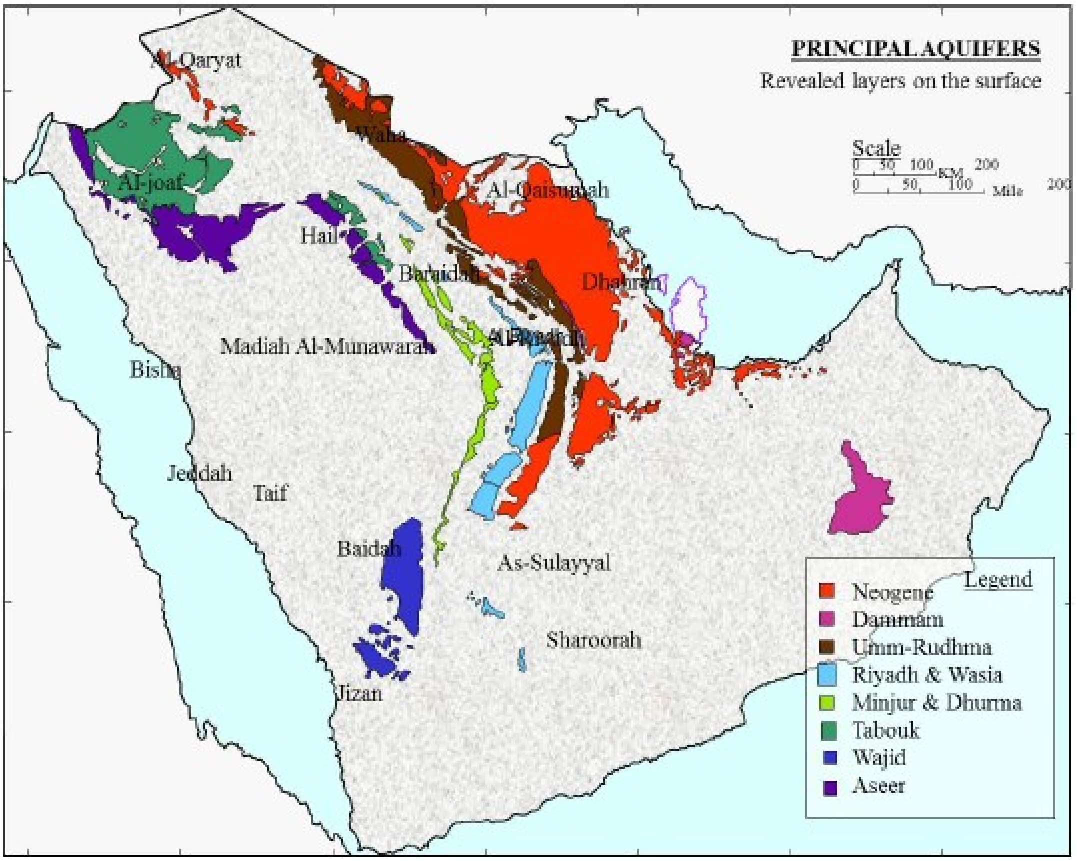


Figure 2.1: Principal aquifers for groundwater in Saudi Arabia [3].

2.2.1.2 Renewable Groundwater

The renewable GW is stored in secondary or shallow alluvial aquifers. These aquifers are usually unconfined, have small area and water tables, which rapidly respond to local precipitations. These aquifers extend mostly over southwestern regions of Saudi Arabia and have variable thickness exceeding up to 100 m, with width varying between 1 and 2 km. Some of the secondary aquifers are: Al-Jauf, Al-Khuff, Al-Jilh, the upper Jurassic, Sakaka, the lower Cretaceous, Aruma, Basalts and Wadi Sediments (Figure 2.2). Water from these aquifers shapes the main source in western Saudi Arabia. It is used for domestic and irrigation proposes and for some of the rural regions, for drinking purposes. Although, the renewable GW is limited in quantity, yet it can be replenished more recurrently and more rapidly than the fossil GW [10]. The total internal renewable GW was estimated to be 2.4 BCM/year [5].

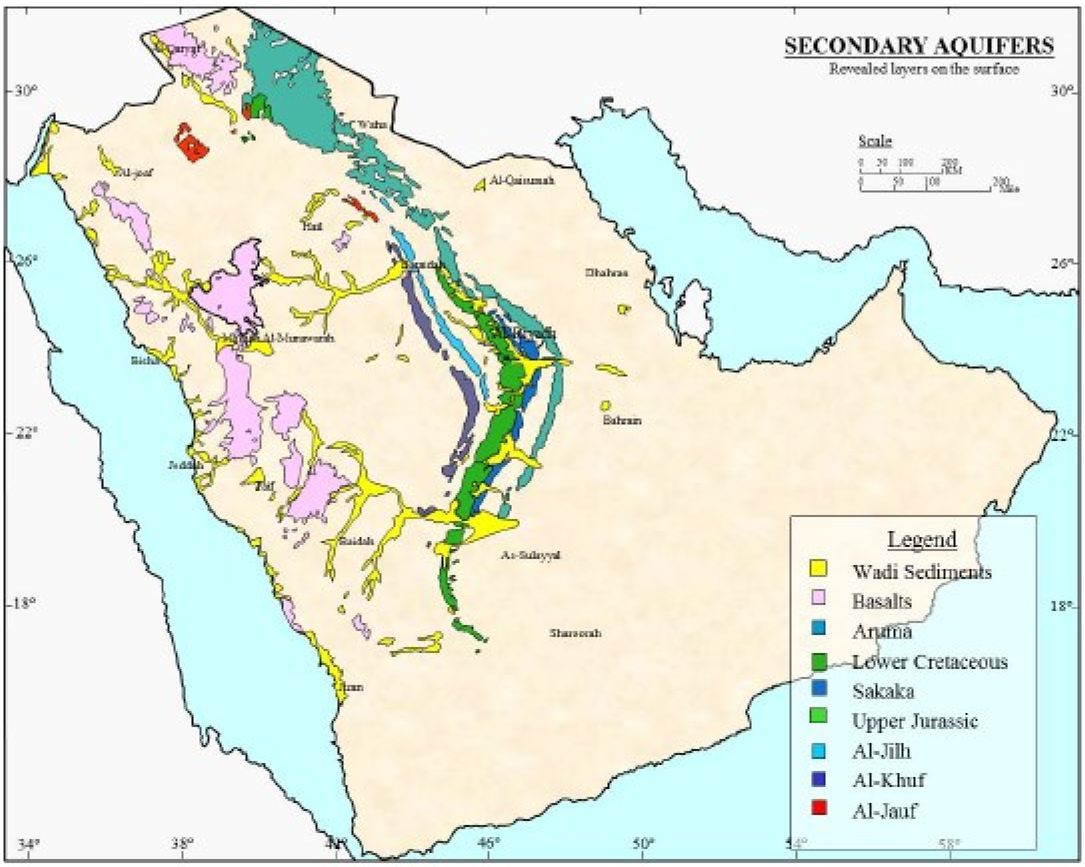


Figure 2.2: Secondary aquifers for groundwater in Saudi Arabia [3].

2.2.2 Surface Water

The source of SW is seasonal rainfalls. In the northern part, annual rainfall ranges between < 100 – 200 mm, while in the south, 500 mm/year rainfall is not uncommon [5]. The long-term average rainfall in the country was estimated to be approximately 125 mm/year, in which most of this rainfall occurs in the south and southwestern regions of the country [5]. The total runoff was approximated to be 2.2 BCM/ year, a part of it infiltrates to recharge the shallow aquifers, whereas some is evaporated [14]. Approximately 60% of the total runoff occurs in western region where the area represents only 10% of the total area of the country, while the residual 40% occurs in the extreme south of the western coast (Tahama), which covers approximately 2% of the total land area [5].

To facilitate storage and recharge, a total of 394 dams across the country store approximately 1.9 BCM per year of surface runoff [21]. The regional details of these dams, their purposes and capacities are presented in Table 2.1. Among these dams, 347 dams with capacity of approximately 1.5 BCM/year were constructed for GW recharges and control. A total of 45 dams store 392.8 MCM/year of water for drinking purposes, whilst 2 dams are used to store 51.5 MCM/year for agricultural purposes (Table 2.1).

Table 2.1: Summary of dams, their purposes and storage capacities across Saudi Arabia (Capacity in MCM/year) [21, 31].

Region	Distribution by purpose									
	Recharge		Flood control		Drinking		Irrigation		Total	
	No. of dams	Design Capacity	No. of dams	Design Capacity	No. of dams	Design Capacity	No. of dams	Design Capacity	No. of dams	Design Capacity
Riyadh	57	75.5	20	20.3					77	95.9
Makkah	30	60.2	10	670.2	3	43.8			43	774.2
Madinah	20	30.1	8	69.6					28	99.7
Qaseem	10	5.9	1	1.3					11	6.7.19
Eastern Region										
Aseer	63	365.2	18	19.3	27	45.7			108	430.2
Hail	28	14.9	3	1.8					31	16.7
Tabouk	10	7.2							10	7.2
Al-Baha	27	10.5	3	0.1	6	48.4	1	0.5	37	59.6
Northern Borders	8	20.9							8	20.9
Al-Jouf	5	6.6	5	8.0					10	14.6
Jazan	1	0.3	1	0.2	8	254.6	1	51.0	11	306.0
Najran	14	6.9	5	87.7	1	0.3			20	94.9
Total	273	604.1	74	878.5	45	392.8	2	51.5	394	1919.7

Table was generated using data of 2011.

2.2.3 Desalinated Water

Saudi Arabia is one of the largest users of desalinated water (DW) in the world. In 1980, the country produced approximately 7.7 MCM of DW [22]. During the period from 1980 to 2011, Saudi Arabia has a total of 30 desalination plants in operation, located on the Arabian Gulf and the Red Sea coasts [16, 22].

The Saline Water Conversion Corporation (SWCC) reported that the total production of DW in 2006 and 2009 was 1033 and 1055.1 MCM, respectively, which has been increased to approximately 1476 MCM in 2011 [10, 21, 22]. The Ninth Development of the Ministry of Economy and Planning reported that desalinations plants in the country produced approximately 1070 and 1048 MCM in 2004 and 2009, respectively, and projected to produce about 2070 MCM in 2014 [16]. The summary of major desalination plants, their productions, desalination approaches, commission dates and years of service can be found in SWCC. The SWCC shows that a total of fourteen plants have already spent 25 years of service lives. The country is planning to produce more DW by constructing additional plants in the near future [16, 22]. DW is mainly used for domestic purposes in the major regions, such as Riyadh, Makkah, Madinah, Qaseem, Eastern Region, Aseer, Tabouk and Jazan [3]. Noteworthy, the seawater desalination plants in Saudi Arabia satisfy more than 50% of the total domestic water demands in the country [17]. Generally, the DW is blended with GW and disinfected before supplying to the consumers [3].

2.2.4 Treated Wastewater

Treated wastewater (TWW) can be a potential source of water supply for agricultural, industrial and landscaping purposes. Recycle of TWW is in practice in many countries, including Saudi Arabia [5]. However, major fractions of TWW in Saudi Arabia is discharged into sand dunes, empty wadies or the Arabian Gulf and Red Sea [3]. The wastewater is treated in about 81 sewage treatment plants in the country [21]. The details of wastewater treatment plants, wastewater generation, TWW and reused TWW across Saudi Arabia are summarized in Table 2.2. The Ministry of Water and Electricity (MOWE) in Saudi Arabia reported that the annual capacity of these plants is approximately 1729.5 MCM, while quantity of wastewater generation, TWW and reused TWW in the country were approximately 1956.7, 1225.2 and 224.3 MCM, respectively (Table 2.2). This means, about 62.6% of the generated wastewater was treated; while only 18.3% of the TWW was recycled for reuse [21]. Chowdhury and Zahrani [3] reported that more than 1500 MCM of domestic wastewater was generated in 2008, while approximately 730 MCM/year was treated. The MOEP of Saudi Arabia reported that 325 MCM of TWW was recycled for reuse in 2009 [16], which is much higher than the values reported in MOWE. It is projected that about 570 MCM of TWW will be available for reuse in 2014 [16].

Table 2.2: Details of wastewater treatment plants, wastewater generation, TWW and reused TWW across Saudi Arabia [21].

Region	Wastewater treatment plants		Wastewater generation		Treated wastewater (TWW)			Reused TWW		
	No. of plants	Design capacity (MCM/year)	Quantity (MCM/year)	Ratio to total quantity (%)	Quantity (MCM/year)	Ratio to total quantity (%)	Ratio to generation (%)	Quantity (MCM/year)	Ratio to total quantity (%)	Ratio to TWW (%)
Riyadh	13	345.8	599.0	30.6	311.5	25.4	52.0	80.3	35.7	25.8
Makkah	14	357.0	490.9	25.1	216.0	17.6	44.0	34.8	15.5	16.1
Madinah	1	109.5	123.4	6.3	87.6	7.1	71.0	0.4	0.2	0.5
Qaseem	5	52.6	93.1	4.8	44.7	3.6	48.0	13.4	6.0	30.0
Eastern Region	21	651.7	472.1	24.1	472.1	38.5	100.0	73.5	32.6	15.6
Aseer	18	133.8	50.4	2.6	34.8	2.8	69.0	17.5	7.8	50.3
Hail	1	4.4	22.6	1.2	6.2	0.5	30.0			
Tabouk	1	21.9	45.1	2.3	32.9	2.7	73.0	0.8	0.4	2.4
Al-Baha										
Northern Borders	2	8.8	13.7	0.7	3.7	0.4	27.0			
Al-Jouf	2	14.6	32.3	1.6	8.4	0.7	26.0			
Jazan	2	7.5	14.1	0.7	7.3	0.7	55.0	4.1	1.8	56.2
Najran	1	21.9								
Total	81	1729.5	1956.7	100.0	1225.2	100.0	62.6	224.8	100.0	18.3

Table was generated using data of 2011.

2.3 Trends of Water Consumptions in Saudi Arabia

2.3.1 Domestic Water Demands

During 1972 to 2013, populations in Saudi Arabia have increased from 6.9 million to 30 million [9]. The MOWE reported that the domestic water demands in 1970 and 2010 were 200 MCM and 2063 MCM, respectively [10]. The FAO estimated the domestic water demands in 2006 to be approximately 2130 MCM [5]. Chowdhury and Zahrani [3] approximated the domestic water demands as 1966, 2307 and 2704 MCM for the years 2004, 2009 and 2014, respectively. During the same years, the Ninth Development Plan of the MOEP reported the domestic water demand as 2100, 2330 and 2583 MCM respectively [16]. The data indicate that the domestic water demands might increase at a rate of 2.1%/year [16].

Between 1999 and 2008, total number of subscribers to domestic water systems increased from 687813 to 844243, reflecting an average increase of 2.5% /year; while the consumption of municipal water per subscriber was reported to be 1391.1 and 3818.1 m^3 respectively [12]. The per capita water use was reported to be approximately 250 liter per capita per day (LPCD) [11]. The MOWE reported that the use of domestic water in 2011 was approximately 235 LPCD [21]. The averages per capita use of municipal water in different regions of Saudi Arabia are shown in Table 2.3.

Table 2.3: Per capita domestic water consumptions (LPCD) in different regions of Saudi Arabia [21].

Region	Per capita use
Riyadh	292
Makkah	237
Madinah	219
Qaseem	252
Eastern Region	370
Aseer	85
Hail	110
Tabouk	174
Al-Baha	61
Norther Borders	136
Al-Jouf	240
Jazan	31
Najran	47
Saudi Arabia	235

2.3.2 Agricultural Water Demands

In 1990s, Saudi Arabia witnessed comprehensive evolutions in agricultural sectors [32]. Between 1975 and 1992, the total cultivated area showed increasing trend [32]. However, since late nineties, the cultivated areas were reduced, possibly due to water shortage in different regions and/or government policy [12]. Majority of the areas were allocated for wheat, fodder crops, fruits, dates and vegetables [12]. For instance, the SSYB reported the cultivated area in 2005, 2006 and 2007 as 1.11, 1.07 and 1.07 million hectares (Mha) respectively, where approximately 0.489, 0.468 and 0.450 Mha of it was allocated for wheat cultivation [12]. Figure 2.3 presents the cultivated area for each region in 2009 [12]. It is to be noted that Riyadh region dominates the cultivated areas followed by Qaseem, Al-Jouf, Jazan, Hail, Eastern region, Tabouk, Makkah, Madinah, Aseer, Najran, Al-Baha and Northern borders (Figure 2.3).

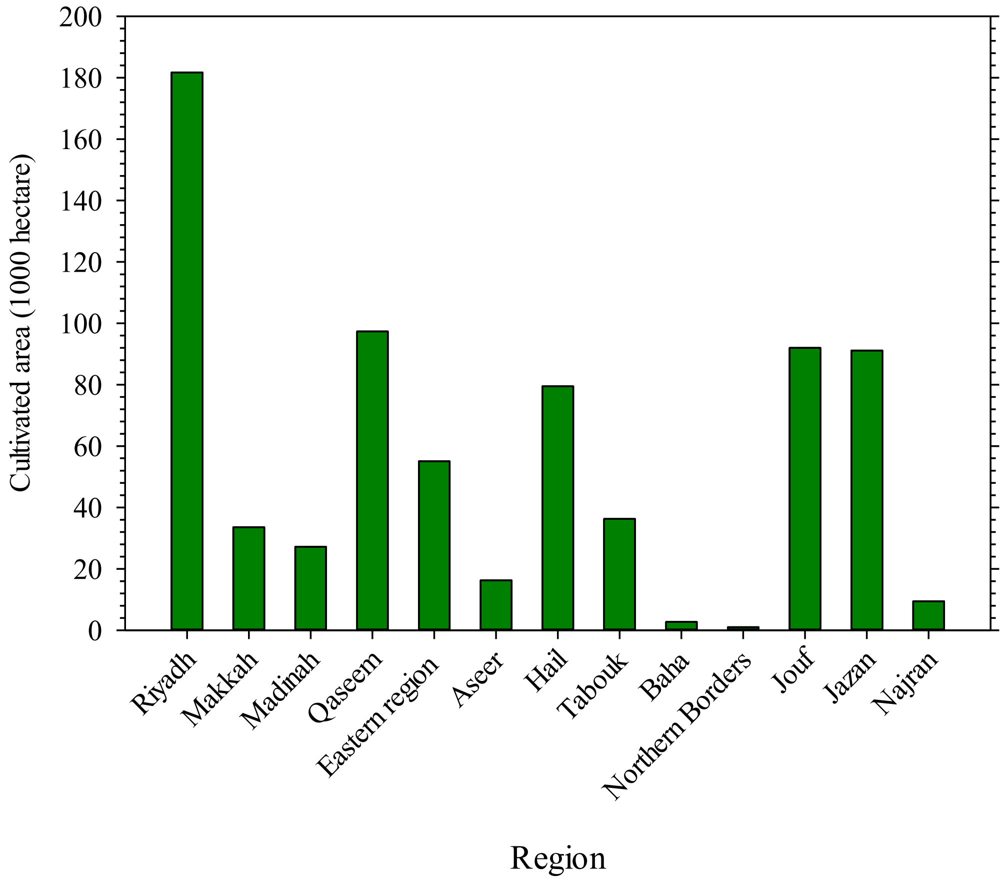


Figure 2.3: Cultivated areas in 2009 for different crops in different regions of Saudi Arabia [8, 33].

Agricultural water in Saudi Arabia are satisfied by non-renewable GW resources, surface and renewable water resources and TWW [34]. The agricultural water demand constitutes more than 80% of the total water demands [5, 14, 16, 18]. The agricultural water demand increased from about 6108 MCM in 1970 to about 9470 and 18000 MCM in 1980 and 1990, respectively [10]. The MOEP reported that the agricultural water demand in 2004 and 2009 was 17530 and 15464 MCM respectively [16]. Ouda [35] reported that the agricultural water demands was 14920 MCM in 2010. In 2014, these demands are projected to be 12794 [16]. The MOEP reported that the total agricultural water demands might decrease at a rate of 3.7%/year between 2009 and 2014.

2.3.3 Industrial Water Demands

The industrial sectors mainly contain petrochemicals, cement, steel, fertilizers, mining, basic metals, textiles and food and beverage productions [10]. The industrial water demand has increased at a rate of about 7.5%/year during the past two decades [10, 36]. This demand has increased from approximately 56 MCM in 1980 to approximately 190 MCM in 1990 [10, 36]. In 2006, the FAO reported that the industrial water demand was 710 MCM [5]. During the period of 2004-2009, industrial water demand was increased from 640 to 713 MCM, indicating a growth rate of 2.2%/year. However, during 2009 - 2014, growth rate of industrial water demand was approximated to be 5.5%/year, which may lead to 930 MCM by 2014 [16]. Chowdhury and Zahrani [3] indicated that the demand in 2014 may be approximately 905 MCM.

2.4 Costs of Using Water from Different Sources

Al-Layla et al. [37] reported that the cost of pumping GW varied from 0.49 to 1.5 SR /m^3. Previous studies reported that the cost of GW treatment is in the range of 1.5 – 4.01 SR/m^3 [37]. Elhadj [11] reported that the overall cost of supplying GW can be in the range of 1.61-2.1 SR/m^3 with an average of 1.84 SR/m^3.

The Saline Water Conservation Cooperation (SWCC) showed that the total production and transmission cost of DW increased from about 3.26 SR/m^3 in 2006 to about 4.09 SR/m^3 in 2010 [38]. However, Elhadj [11] reported the average cost of using DW from the small, medium and large plants as 8.89 SR/m^3, including capital cost (1.43 SR/m^3), operation, maintenance, administrative and depreciation charges (2.51 SR/m^3) and transportation cost (4.95 SR/m^3). Recent studies have demonstrated that the average cost of producing and transporting DW are 2.25 and 2.66 SR/m^3, respectively, with total cost of 4.91 SR/m^3 [39].

The cost of reusing TWW differs with the type of treatment (e.g., secondary or tertiary), collection and recycling [40]. Lee et al. [41] reported the average cost of treating wastewater as 2 SR/m^3 (range: 1.73 – 2.48 SR/m^3). Al-Aama and Nakhla [42] reported the overall cost of TWW reuse for Jubail plant, Saudi Arabia, as 7.61 SR/m^3. The cost included capital cost (5 SR/m^3), tertiary treatment (0.6 SR/m^3), collection (1.13 SR/m^3) and distribution (0.23 SR/m^3). Zahid [43] estimated the cost of different approaches of domestic wastewater treatment in Riyadh, Saudi Arabia, where the capital cost was in the range of 0.94 - 1.05 SR/m^3 and the operation and maintenance cost was in the range of 0.11 – 0.19 SR/m^3. Chowdhury and Zahrani [40] used the overall cost for reusing TWW as 3.08 SR/m^3. Kajenthira et al [39] reported the overall cost of reusing secondary TWW in the range of 0.49 -3.36 SR/m^3, whereas the total cost of tertiary TWW was in the range of 4.46 – 7.61 SR/m^3.

2.5 Multi-Objective Optimization Models

The models express a set of mathematical relationships, equations, logical dependence etc. [44]. Models often assist in decision analysis for the real-life problems. The analysis of decision-making considers situations varying from single objective to multiple objectives [45]. The baseline model is the starting point, which can deal with the traditional single objective linear programming or a complex multi-objective linear programming model [46].

The decision making problem with several conflicting objectives is called a multi-objective optimization problem [47]. Multi-objective decision making (MODM) was originally innovated by Kuhn and Tucker [48]. MODM has the following features [49] as:

1) Multi-objective programming encourages in developing more convenient roles for the decision-makers in the planning and decision-making processes.
2) When multi-objective approach is adopted, a broad range of alternatives is generally specified.
3) Models and understanding the problem analysis will be more realistic when multiple objectives are considered.

2.6 Applications of Multi-Objective Models in Water Resources

Multi-objective models can be applied to overcome the complexity in sector wise water allocations. Han et al. [50] developed a multi-objective linear programming model with interval parameters for water resources allocation in Dalian city of China. They devised a plan on sector wise water allocations for the years 2010, 2015 and 2020. Oscar et al. [51] adopted multi-criteria analysis for designing water supply network in southern France. The model generation included 4 decision-makers, 13 criteria and 38 alternatives. The methodology comprised of two steps. The first step addressed an overview of all probable alternatives, where ELECTRE III technique was used for reducing the 38 alternatives to 8 in order to study them thoroughly. In the second step, using ELECTRE III technique, the model tested whether the minimized number of alternatives in the first step could be interpreted. However, the methodology adopted in this study lack the operational concepts for negotiations, such as possible tradeoffs between decision-makers. Lee et al. [52] applied a stochastic model for river water quality. The model included the variable flow and SW quality in terms of salinity. The model was generated by amending the series differential equations involving large-scale hydrological model. El Magnouni et al. [53] presented a multi-criteria decision aid technique for GW quality management. Their objectives were to evaluate the hydrodynamic behavior of the GW and to investigate the management scenarios. In this study, to better allocate water resources for different sectors in different regions of Saudi Arabia, a multi-objective optimization model has been developed using the goal programming (GP) technique.

CHAPTER 3

METHODOLOY

3.1 Introduction

Multi-objective optimization model is a mathematical and systematic approach that has been applied to solve many decision problems including water resources allocations and water pricing. There are many techniques to develop a multi-objective optimization model. In this study, the goal programming (GP) has been adopted. The GP has several advantages [54, 55]:

1) GP deals with mathematical expressions for both objectives and constraints.
2) GP allows for an ordinal ranking for goals, where the higher priority goals are achieved prior to the lower priority goals.
3) GP is useful in situations where the multiple conflicting objectives cannot be fully satisfied.
4) GP technique attempts to minimize the deviations from the goals.
5) In complex situations with multiple objectives and constraints, it is usually infeasible to have an optimal solution with all constraints being satisfied. However, GP provides the decision-maker with an option of specifying priorities and sub-priorities (weights) to identify the preference structure, and GP model will try to obtain an optimal solution.

3.2 Goal Programming

Goal programming (GP) model is one of the commonly used multi-objective optimization techniques for decision analysis. GP was originally developed by Charnes and Cooper in 1961 [56]. GP model allows the decision-makers to incorporate multiple considerations into the model through the determination of aspiration levels and their priorities [55]. It includes a set of constraints and a set of goals, which are prioritized according to their importance [57]. GP can be classified based on the types of mathematical programming, such as, linear programming, integer programming and nonlinear programming [58]. In this study, only the linear goal programming model is adopted.

GP has been applied in many contemporary analyses concerning water resources management. Mohan and Jayant applied GP to discuss the application of a multipurpose reservoir project in India [59]. Two GP models were formulated and applied to the Bhadra reservoir for possible irrigation and hydropower uses. Al-Layla et al. [60] used the GP for making a survey of water resources and water uses in Saudi Arabia. The model was developed with the objectives of satisfying demands, minimization of GW consumption and minimization of the total cost of water production. The constraints of the model included the resources and demands for various purposes. The input parameters for demands and supplies were assumed to be constant. Dandy and Crawly studied the development of an operation policy for a multiple reservoir system using GP taking water quality into consideration [61]. Alidi and Al-Faraj [62] developed a multi-objective GP model for optimal allocation of DW to different water blending stations

(WBS) in Dammam city of Saudi Arabia. The multi-objectives of the model were to satisfy the demands for the blending water, control the salinity level, minimize the GW depletion, satisfy the brackish water demands at different WBS and minimize the overproduction of DW. The constraints of the model were the production capacity of desalination plants, the extraction rate from the GW wells and the required salinity level at WBS. Al-Zahrani and Abid [63] used stochastic GP model for optimal blending of DW with GW in Eastern Region of Saudi Arabia. The study considered 9 WBS, 13 GW wells and 2 large desalination plants of the study region. The WBS was assumed to be control point in the system. The model had five objectives as: (1) satisfy the demands of blended water at different blending stations, (2) control the salinity of blended water at each blending station with the required salinity of 500 part per million (ppm) as a maximum level, (3) minimize the depletion level of brackish GW, (4) satisfy the demand of brackish water at different stations, and (5) minimize overproduction of DW. The developed model involved 22 decision variables, 84 deviational variables and 42 linear constraints.

3.3 Model Development

The development of GP model is very similar to that of linear programming model [64]. GP model extends the linear programming development to accommodate mathematical programming with multi-objectives [56]. The major differences are specific considerations of goals and the different priorities with the different goals. The basic framework for developing the multi-objective model in this study is shown in Table 3.1.

Table 3.1: Modeling framework for multi-sources multi-users water distributions.

Water demand sector	Domestic (D) $Q^{D},\ TDS^{D}$	Agricultural (A) $Q^{A},\ TDS^{A}$	Industrial (I) $Q^{I},\ TDS^{I}$
Water supply source			
Groundwater (GW) $Q^{GW},\ TDS^{GW}, C^{GW}$	q_{D}^{GW}	q_{A}^{GW}	q_{I}^{GW}
Surface water (SW) $Q^{SW},\ TDS^{SW}, C^{SW}$	q_{D}^{SW}	q_{A}^{SW}	-
Desalinated water (DW) $Q^{DW},\ TDS^{DW}, C^{DW}$	q_{D}^{DW}	-	-
Treated wastewater (TWW) $Q^{TWW},\ TDS^{TWW}, C^{TWW}$	-	q_{A}^{TWW}	-

Definitions of these parameters are shown in the list of notations.

The sub-sections below describe each component of model development [64, 65]:

3.3.1 Objective Function

The objective function in GP model is always minimized and is composed of deviational variables only. It minimizes the deviations of the optimal solution from target goals, prioritized and weighted. In this study, the objective function was developed to:

i. Satisfy domestic, agricultural and industrial water demands in different regions of Saudi Arabia.
ii. Control quality of water with the desired quality level in terms of total dissolved solids (TDS).
iii. Maximize reuse of TWW.
iv. Maximize use of SW.
v. Minimize extraction of GW in order to maximize GW conservation.

vi. Minimize overproduction of DW considering that the available DW is completely used.

vii. Minimize the overall cost of using water from different supply sources.

3.3.2 Decision Variables

The decision variables represent of the sources that supply water to different sectors. These are:

- GW to domestic, agricultural and industrial sectors.
- SW to domestic and agricultural sectors.
- DW to domestic sector.
- TWW to agricultural sector.

3.3.3 Deviational Variables

The deviational variables can either be positive or negative. The positive deviation indicates an over-achievement of a goal and the negative deviation represents the under-achievement of that goal. Both positive and negative deviations cannot occur simultaneously.

3.3.4 Model Constraints

The model constraints related to this study include the following:

i. Supply constraints are the annual available water from different sources (MCM/year).

ii. Demands constraints represent the annual water demands (MCM/year).

iii. Quality constraints represent the existing TDS (ppm) of available water from different resources, and the required TDS (ppm) of water at various demands sectors.

iv. Cost constraints represent the cost (million US$/year) of using the available water from different sources.

v. Non-negativity constraints ensure that the decision and deviational variables have non-negative values.

3.3.5 Goals of the Model

The goals of the model related to this study are presented in Table 3.2.

3.3.6 Goals Prioritization

Different goals are ranked based on their importance, so that the goals of primary importance receive first-priority, those of secondary importance receive the second-priority, and so on. In this study, the proposed model considers the following priorities according to their importance:

R_1: To satisfy the demand of domestic water (minimization of positive and negative deviations).

R_2: To control domestic water quality within the allowable level of TDS (minimization of positive deviations).

P_3: To satisfy the demand of agricultural water (minimization of positive and negative deviations).

R_4: To control the quality of agricultural water within the desired quality in terms of TDS (minimization of positive deviations).

R_5: To satisfy the demand of industrial water (minimization of positive and negative deviations).

R_6: To control the quality of industrial water within the desired quality level in terms of TDS (minimization of positive deviations).

R_7: To maximize the reuse of TWW (minimization of negative deviation), while any demand more than the available TWW will not be satisfied (minimization of positive deviation). The quantity of TWW was considered to be equal to the quantity of generated wastewater (full treatment), which is the predicted quantity to achieve the third objective. The existing capacities of treatment plants are compared to the predicted quantity to develop future plan.

R_8: To maximize use of SW (minimization of negative deviation) considering that any demand above the finite quantity of SW will not be satisfied (minimization of positive deviation).

R_9: To minimize extraction of GW in order to minimize the GW table depletion (minimization of positive deviation).

R_{10}: To minimize the overproduction of DW considering that the available DW is fully used (minimization of positive deviation).

R_{11}: To minimize the cost of water use from various sources (minimization of positive deviations).

To incorporate the priorities in the model, arbitrary weights were assigned for these priorities. It is to be noted that no standard approach is available for assigning relative weights. In this study, highest priority was assigned to R_1 while the lowest was for R_{11}. The corresponding weights are W_1 to W_{11} with the following values:

$W_1 = 100$; $W_2 = 95$; $W_3 = 80$; $W_4 = 75$; $W_5 = 60$; $W_6 = 55$; $W_7 = 45$; $W_8 = 35$; $W_9 = 25$; $W_{10} = 15$; $W_{11} = 5$.

Where W_i is the assigned weight given to indicate the importance of the ith priority ($i = 1, 2, 3\ldots 11$).

Using the parameters in Table 3.1 and the priorities, the multi-objective GP model was developed as shown in Table 3.2.

Table 3.2: Model development considering all components and aspiration levels.

Priority (R)	Weight (W)	Model objectives		Decision variables	Deviational variables	Model constraints	Model goals	Objective function
R_1	W_1=100	Satisfying domestic water demands		q_D^{GW} q_D^{SW} q_D^{DW}	N_D P_D	Q^D	$q_D^{GW} + q_D^{SW} + q_D^{DW} + N_D - P_D = Q^D$	Min $N_D + P_D$
R_2	W_2=95	Satisfying domestic water quality	Blended water GW+DW	q_D^{GW} q_D^{DW}	$N_{D(blend)}^{TDS}$ $P_{D(blend)}^{TDS}$	TDS^D	$\frac{q_D^{GW} TDS^{GW} + q_D^{DW} TDS^{DW}}{q_D^{GW} + q_D^{DW}} + N_{D(blend)}^{TDS} - P_{D(blend)}^{TDS} = TDS^D$	Min $P_{D(blend)}^{TDS}$
			GW	q_D^{GW}	$N_{D(GW)}^{TDS}$ $P_{D(GW)}^{TDS}$	TDS^D	$TDS^{GW} + N_{D(GW)}^{TDS} - P_{D(GW)}^{TDS} = TDS^D$	Min $P_{D(GW)}^{TDS}$
			SW	q_D^{SW}	$N_{D(SW)}^{TDS}$ $P_{D(SW)}^{TDS}$	TDS^D	$TDS^{SW} + N_{D(SW)}^{TDS} - P_{D(SW)}^{TDS} = TDS^D$	Min $P_{D(SW)}^{TDS}$
R_3	W_3=80	Satisfying agricultural water demands		q_A^{GW} q_A^{SW} q_A^{TWW}	N_A P_A	Q^A	$q_A^{GW} + q_A^{SW} + q_A^{TWW} + N_A - P_A = Q^A$	Min $N_A + P_A$
R_4	W_4=75	Satisfying agricultural water quality	GW	q_A^{GW}	$N_{A(GW)}^{TDS}$ $P_{A(GW)}^{TDS}$	TDS^A	$TDS^{GW} + N_{A(GW)}^{TDS} - P_{A(GW)}^{TDS} = TDS^A$	Min $P_{A(GW)}^{TDS}$
			SW	q_A^{SW}	$N_{A(SW)}^{TDS}$ $P_{A(SW)}^{TDS}$	TDS^A	$TDS^{SW} + N_{A(SW)}^{TDS} - P_{A(SW)}^{TDS} = TDS^A$	Min $P_{A(SW)}^{TDS}$
			TWW	q_A^{TWW}	$N_{A(TWW)}^{TDS}$ $P_{A(TWW)}^{TDS}$	TDS^A	$TDS^{TWW} + N_{A(TWW)}^{TDS} - P_{A(TWW)}^{TDS} = TDS^A$	Min $P_{A(TWW)}^{TDS}$
R_5	W_5=60	Satisfying industrial water demands		q_I^{GW}	N_I P_I	Q^I	$q_I^{GW} + N_I - P_I = Q^I$	Min $N_I + P_I$
R_6	W_6=55	Satisfying industrial water quality		q_I^{GW}	$N_{I(GW)}^{TDS}$ $P_{I(GW)}^{TDS}$	TDS^I	$TDS^{GW} + N_{I(GW)}^{TDS} - P_{I(GW)}^{TDS} = TDS^I$	Min $P_{I(GW)}^{TDS}$
R_7	W_7=45	Maximizing TWW reuse		q_A^{TWW}	N^{TWW} P^{TWW}	Q^{TWW}	$q_A^{TWW} + N^{TWW} - P^{TWW} = Q^{TWW}$	Min $N^{TWW} + P^{TWW}$
R_8	W_8=35	Maximizing SW supply		q_D^{SW} q_A^{SW}	N^{SW} P^{SW}	Q^{SW}	$q_D^{SW} + q_A^{SW} + N^{SW} - P^{SW} = Q^{SW}$	Min $N^{SW} + P^{SW}$
R_9	W_9=25	Maximizing GW conservation		q_D^{GW} q_A^{GW} q_I^{GW}	N^{GW} P^{GW}	Q^{GW}	$q_D^{GW} + q_A^{GW} + q_I^{GW} + N^{GW} - P^{GW} = Q^{GW}$	Min P^{GW}
R_{10}	W_{10}=15	Minimizing DW overproduction		q_D^{DW}	N^{DW} P^{DW}	Q^{DW}	$q_D^{DW} + N^{DW} - P^{DW} = Q^{DW}$	Min P^{DW}
R_{11}	W_{11}=5	Minimizing water supply costs	GW	q_D^{GW} q_A^{GW} q_I^{GW}	N_{GW}^C P_{GW}^C	$C^{GW} Q^{GW}$	$C^{GW}(q_D^{GW} + q_A^{GW} + q_I^{GW}) + N_{GW}^C - P_{GW}^C = C^{GW} Q^{GW}$	Min P_{GW}^C
			SW	q_D^{SW} q_A^{SW}	N_{SW}^C P_{SW}^C	$C^{SW} Q^{SW}$	$C^{SW}(q_D^{SW} + q_A^{SW}) + N_{SW}^C - P_{SW}^C = C^{SW} Q^{SW}$	Min P_{SW}^C
			DW	q_D^{DW}	N_{DW}^C P_{DW}^C	$C^{DW} Q^{DW}$	$C^{DW} q_D^{DW} + N_{DW}^C - P_{DW}^C = C^{DW} Q^{DW}$	Min P_{DW}^C
			TWW	q_A^{TWW}	N_{TWW}^C P_{TWW}^C	$C^{TWW} Q^{TWW}$	$C^{TWW} q_A^{TWW} + N_{TWW}^C - P_{TWW}^C = C^{TWW} Q^{TWW}$	Min P_{TWW}^C

Definitions of these parameters are shown in the list of notations.

The objective function of the model can be summarized as follows:

Minimize

$$\underbrace{W_1(N_D + P_D)}_{\boldsymbol{R_1}} + \underbrace{W_2(P^{TDS}_{D(blend)} + P^{TDS}_{D(GW)} + P^{TDS}_{D(SW)})}_{\boldsymbol{R_2}} + \underbrace{W_3(N_A + P_A)}_{\boldsymbol{R_3}}$$

$$+ \underbrace{W_4(P^{TDS}_{A(GW)} + P^{TDS}_{A(SW)} + P^{TDS}_{A(TWW)})}_{\boldsymbol{R_4}} + \underbrace{W_5(N_I + P_I)}_{\boldsymbol{R_5}} + \underbrace{W_6 P^{TDS}_{I(GW)}}_{\boldsymbol{R_6}}$$

$$+ \underbrace{W_7(N^{TWW} + P^{TWW})}_{\boldsymbol{R_7}} + \underbrace{W_8(N^{SW} + P^{SW})}_{\boldsymbol{R_8}} + \underbrace{W_9 P^{GW}}_{\boldsymbol{R_9}}$$

$$+ \underbrace{W_{10} P^{DW}}_{\boldsymbol{R_{10}}} + \underbrace{W_{11}(P^C_{GW} + P^C_{SW} + P^C_{DW} + P^C_{TWW})}_{\boldsymbol{R_{11}}} \tag{3.1}$$

Where, R_1-R_{11} represent the corresponding priorities; W_1-W_{11} are the corresponding weights; N with alphabetical sub/super scripts represents the negative deviations; P with alphabetical sub/super scripts represents the positive deviations.

3.4 Uncertainty

Water resources and supplies are associated with uncertainties from various sources, including, resource characterization, demand forecasting, population dynamics, water consumption patterns, policy implications, water quality and cost assessment. Obtaining precise data on these parameters is often difficult. To incorporate uncertainties associated to these parameters, random realizations are generated. To generate random realizations, statistical characteristics of the parameters (e.g., water supply and demand) are investigated. However, historical data are not enough to justify any standard statistical distribution for the input parameters. In this study, random realizations are generated following Normal distribution. The forecasted values of water supplies and demands are considered as the mean values, while the standard deviations are obtained as 20% of the mean values. It is to be noted that larger number of realizations can provide better results. Shareef [66] used a set of 40 random realizations for simulating a multi-objective model. In this study, a set of 100 random realizations was used.

3.5 Model Training

The developed multi-objective optimization model is solved using the LINGO model optimizer. The software was designated for solving linear, nonlinear, quadratic, integer and stochastic optimization models [67]. Figure 3.1 summarizes the steps of model training using the LINGO software. The software provides the values of the objective function, the decision variables and the deviational variables. The zero value of an objective function indicates that the objective is achieved. The negative deviation indicates that there is an excess amount of that constraint, while the positive deviation indicates the additional needs of that variable to satisfy the objectives. The model is applied for the years of 2015 through 2050 at an interval of 5 years.

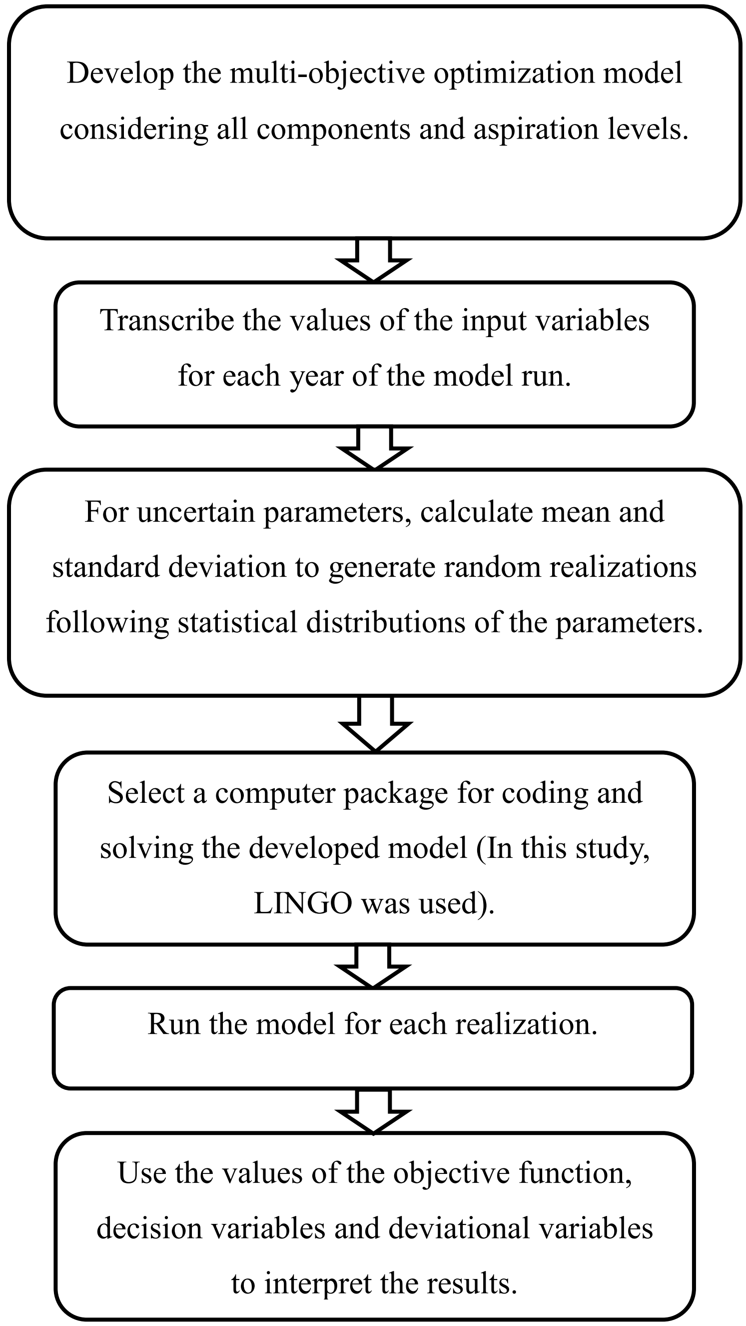


Figure 3.1: Procedure of running the developed multi-objective optimization model.

CHAPTER 4

DATA GENERATION

4.1 Introduction

The multi-objective optimization model developed in the preceding chapter is applied to different regions of Saudi Arabia from 2015 through 2050. The data description and sources are summarized below:

4.1.1 Water Supply

Water supply data were collected from the Ministry of Water and Electricity (MOWE) [17, 20, 21, 68]. The use of water supply from different sources varied widely from region to region. The historical data for GW, SW, DW and TWW in each region of Saudi Arabia are presented in Table 4.1, 4.2, 4.3 and 4.4 respectively. The data show that more than half of extracted GW in the country is consumed by three regions: Riyadh, Qaseem and Jazan. GW extraction shows decreasing trends in all regions except the Northern borders. SW data are shown by amounts utilized from the dams. DW is used for domestic purposes in the major regions (Table 4.3). TWW data indicates that major fraction of TWW remains unused.

Table 4.1: Regional quantities of GW extraction in Saudi Arabia (MCM/year) [17, 20, 21]

Region	2009	2010	2011
Riyadh	4623.9	4474.9	4368.9
Makkah	1093.8	988.4	911.0
Madinah	1053.0	1011.0	979
Qaseem	2366.8	2274.7	2190.7
Eastern Region	1212.4	1179.8	1030.2
Aseer	400.5	390.3	372.3
Hail	1404.0	1351.0	1300.5
Tabouk	799.1	763.4	729.8
Al-Baha	124.0	112.8	100.2
Northern Borders	31.0	31.2	31.5
Al-Jouf	1559.0	1490.7	1425.6
Jazan	1880.9	1755.7	1689.7
Najran	294.0	285.7	278.4
Total	16842.4	16109.5	15407.8

Table 4.2: Regional quantities of SW utilized by dams for different purposes in Saudi Arabia (MCM/year) [17, 20, 21].

Utilization by purpose	Year	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
Recharge	2009	72.9	58.6	20.7	5.2		357.8	11.1	6.6	9.6	20.7		0.3	3.0	566.3
	2010	73.5	59.5	26.0	5.9		359.7	13.2	7.2	10.5	20.9	6.6	0.3	4.9	588.0
	2011	75.5	60.2	30.1	5.9		365.2	14.9	7.2	10.5	20.9	6.6	0.3	6.9	604.1
Flood control	2009	19.1	234.8	64.5	1.3		16.6	1.8		0.1		7.4	0.2	87.1	432.8
	2010	20.3	418.4	69.6	1.3		19.3	1.8		0.1		7.4	0.2	87.7	626.0
	2011	20.3	670.2	69.6	1.3		19.3	1.8		0.1		8.0	0.2	87.7	878.5
Drinking	2009		42.8				36.0			30.5			194.2		303.5
	2010		43.8				42.9			38.6			253.6	0.3	379.3
	2011		43.8				45.7			48.4			254.6	0.3	392.8
Irrigation	2009									0.5			51.0		51.5
	2010									0.5			51.0		51.5
	2011									0.5			51.0		51.5
Total	2009	92.0	336.2	85.2	6.5		410.4	12.8	6.6	40.8	20.7	7.4	245.6	90.1	1354.1
	2010	93.8	521.7	95.6	7.2		421.9	14.9	7.2	49.9	20.9	14.0	305.0	92.9	1644.7
	2011	95.9	774.2	99.7	7.2		430.2	16.7	7.2	59.6	20.9	14.6	306.0	94.9	1926.9

Table 4.3: Regional quantities of distributed DW in Saudi Arabia (MCM/year) [17, 20, 21, 68].

Region	2007	2009	2010	2011
Riyadh	287.4	310.8	335.0	338.0
Makkah	370.7	443.0	539.0	613.0
Madinah	115.4	119.4	126.0	131.0
Qaseem	5.6	6.3	8.0	8.0
Eastern Region	250.4	208.1	187.0	316.0
Aseer	39.5	45.1	49.0	54.0
Hail				
Tabouk	6.2	8.1	9.0	10.0
Al-Baha				
Northern Borders				
Al-Jouf				
Jazan	0.6	0.9	5.0	6.0
Najran				
Total	1075.8	1141.7	1258.0	1476.0

Table 4.4: Details of GWW, TWW and reused TWW in different regions of Saudi Arabia (MCM/year) [20, 21].

Region	2010			2011		
	GWW	TWW	Reused TWW	GWW	TWW	Reused TWW
Riyadh	579.4	278.1	80.3	599.0	311.5	80.3
Makkah	428.8	210.1	36.3	490.9	216.0	34.8
Madinah	121.8	62.1	6.2	123.4	87.6	0.4
Qaseem	92.7	41.7	12.1	93.1	44.7	13.4
Eastern Region	410.8	345.1	73.0	472.1	472.1	73.5
Aseer	46.5	42.3	7.4	50.4	34.8	17.5
Hail	23.3	4.2	0.0	22.6	6.2	0.0
Tabouk	45.6	21.9	0.8	45.1	32.9	0.8
Al-Baha						
Northern Borders	13.3	2.4	0.0	13.7	3.7	0.0
AL-Jouf	30.5	6.4	0.0	32.3	8.4	0.0
Jazan	13.5	7.0	3.0	14.1	7.3	4.1
Najran						
Total	1806.1	1021.3	219.1	1956.7	1225.2	224.8

GWW: Generated wastewater; TWW: Treated wastewater.

4.1.2 Water Demands

The historical data of water demands in the regions of Saudi Arabia were collected from the Ninth Development Plan of the MOEP [16]. The domestic, agricultural and industrial water consumptions are presented in Table 4.5.

Table 4.5: Sector wise water demands in different regions of Saudi Arabia (MCM/year) [16].

Region	2009			2014			Average annual growth rate (%)		
	D	A	I	D	A	I	D	A	I
Riyadh	673	4089	236	752	3467	280	2.2	-3.2	3.5
Makkah	608	861	144	667	737	193	1.9	-3.1	6.0
Madinah	158	968	52	178	775	69	2.4	-4.3	5.8
Qaseem	86	2274	21	96	1866	24	2.2	-3.9	2.7
Eastern Region	353	911	198	387	734	249	1.9	-4.2	4.7
Aseer	124	350	16	137	330	24	2.0	-1.2	8.4
Hail	45	1352	7	50	1099	18	2.1	-4.1	20.8
Tabouk	67	733	8	75	565	15	2.3	-5.1	13.4
Al-Baha	30	120	5	32	100	11	1.3	-3.6	17.1
Norther Borders	24	4	3	27	6	3	2.4	8.4	0.0
Al-Jouf	39	1510	10	43	1196	12	2.0	-4.6	3.7
Jazan	86	2040	8	97	1712	20	2.4	-3.4	20.1
Najran	37	252	5	42	207	12	2.6	-3.9	19.1
Total	2330	15464	713	2583	12794	930	2.1	-3.7	5.5

D: Domestic; A: Agricultural; I: Industrial.

4.1.3 Water Quality

The quality of water varies from source to source. There is a large variation in GW quality among different aquifers in the country. Water quality is often indicated by the total dissolved solids (TDS). Al-Zahrani and Abid reported that TDS could vary in the range of 300 to more 10000 ppm [63]. Data on the quality of SW is limited [69]. The salinity of DW in terms of TDS was reported to be 50 ppm [63], while the TDS of TWW effluent was 2000 ppm [40]. In this study, the desired TDS for domestic, agricultural and industrial purpose has been set at a maximum level of 500, 3500 and 2000 ppm respectively [40, 63]. Table 4.6 shows the further details.

Table 4.6: The quality aspects of the aspiration level in the model [40, 63].

Water supply		Water consumption	
Source	Average TDS (ppm)	Sector	Maximum allowable TDS (ppm)
Deep GW	3500	Domestic	500
Shallow GW	300	Agricultural	3500
SW	225	Industrial	2000
DW	50		
TWW	2000		

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater; TDS: Total dissolved solids.

4.1.4 Water Costs

This study used the overall average cost of supplying GW as 1.84 SR/m^3. Data on the cost of SW is limited [69]. In this study, average cost of using SW was assumed to be 1.84 SR/m^3. The cost of using DW was reported to be in the range of 4.91 – 8.89 SR/m^3 with an average cost of 6.9 SR/m^3 [11, 38, 39]. In this study, average cost using DW was assumed to be 6.9 SR/m^3. Past data indicate that the cost of TWW reuse ranges between 3.08-7.61 SR/m^3 with an average cost of 5.36 SR/m^3 [39-43, 70]. This study has used an average cost of 5.36 SR/m^3 for reusing TWW.

4.2 Data Forecasting

4.2.1 Water Supplies Forecasting

The GW, SW and DW were assumed to be constant to the levels of 2011 [21]. Reuse of TWW was considered to be equal to the forecasted generated wastewater (GWW), considering the full treatment and recycling of GWW. The GWW was predicted as 80% of domestic water consumption. The input parameters for source wise water supplies from 2015 through 2050 in different regions of Saudi Arabia are presented in Table 4.7 and 4.8.

Table 4.7: Source wise water supplies from 2015 through 2050 in different regions of Saudi Arabia (MCM/year) [21].

Region	GW	[a] SW	DW	[b] TWW
Riyadh	4368.9		338.0	345.8
Makkah	911.0	43.8	613.0	357.0
Madinah	979.0		131.0	109.5
Qaseem	2190.7		8.0	52.6
Eastern Region	1030.2		316.0	651.7
Aseer	372.3	45.7	54.0	133.8
Hail	1300.5			4.4
Tabouk	729.8		10.0	21.9
Al-Baha	100.2	48.9		
Northern Borders	31.5			8.8
Al-Jouf	1425.6			14.6
Jazan	1689.7	305.6	6.0	7.5
Najran	278.4	0.3		21.9
Total	15407.8	444.3	1476.0	1729.5

[a] Capacities of dams that constructed for drinking and irrigation purposes; [b] the existing capacities of wastewater plants; GW: Groundwater; SW: surface water; DW: Desalinated water, TWW: Treated wastewater.

Table 4.8: Forecast of generated wastewater in different regions of Saudi Arabia (MCM/year).

Year	Riyadh	Makkah	Madinah	Qaseem	Eastern Region	Aseer	Hail	Tabouk	Al-Baha	Northern Borders	Al-Jouf	Jazan	Najran	Total
2015	613.5	544.6	145.8	78.4	316.2	111.7	40.8	61.4	25.9	22.1	35.1	79.3	34.5	2109.3
2020	684.0	598.3	164.1	87.4	347.4	123.3	45.2	68.8	27.7	24.9	38.8	89.3	39.3	2338.5
2025	762.6	657.3	184.7	97.5	381.6	136.2	50.2	77.1	29.5	28.1	42.8	100.6	44.6	2592.9
2030	850.3	722.2	208.0	108.7	419.3	150.4	55.7	86.4	31.5	31.6	47.3	113.2	50.7	2875.2
2035	948.0	793.5	234.2	121.1	460.7	166.0	61.8	96.8	33.6	35.6	52.2	127.5	57.7	3188.6
2040	1057.0	871.8	263.7	135.1	506.1	183.3	68.6	108.5	35.8	40.0	57.6	143.5	65.6	3536.6
2045	1178.5	957.8	296.9	150.6	556.1	202.4	76.1	121.5	38.2	45.1	63.6	161.6	74.6	3922.9
2050	1314.0	1052.3	334.2	167.9	611.0	223.4	84.4	136.2	40.8	50.8	70.3	181.9	84.8	4351.9

4.2.2 Water Demands Forecasting

The domestic, agriculture and industrial water demands are shown in Table 4.9. The future domestic water demands were obtained using the average annual growth rate (Table 4.5) [16]. The Ninth Development Plan of the MOEP [16] showed a reduction in Saudi agricultural water demand during 2009 through 2014 by an average rate of 3.7%/year (Table 4.5). Agricultural water demand was assumed to be constant to the level of 2014 [17]. The growth in industrial water demands are shown in Table 4.5 [16]. The data showed that the average annual growth rate of industrial water demand in Saudi Arabia was 5.5%/year. In this study, similar rate was used for forecasting the industrial water demand.

Table 4.9: Forecast of sector wise water demands in different regions of Saudi Arabia (MCM/year) [16].

Year	Sector	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	D	766.9	680.7	182.2	98.0	395.2	139.6	51.0	76.8	32.4	27.7	43.9	99.2	43.2	2636.6
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	325.4	198.6	71.7	29.0	273.0	22.1	9.7	11.0	6.9	4.1	13.8	11.0	6.9	983.1
2020	D	855.0	747.9	205.1	109.3	434.2	154.2	56.6	86.0	34.6	31.2	48.5	111.6	49.1	2923.1
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	425.3	259.5	93.7	37.8	356.8	28.8	12.6	14.4	9.0	5.4	18.0	14.4	9.0	1284.9
2025	D	953.3	821.7	230.9	121.8	477.0	170.2	62.8	96.4	36.9	35.1	53.5	125.7	55.8	3241.1
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	555.8	339.2	122.5	49.5	466.3	37.7	16.5	18.8	11.8	7.1	23.6	18.8	11.8	1679.3
2030	D	1062.9	902.7	260.0	135.8	524.1	187.9	69.6	108.0	39.3	39.5	59.1	141.5	63.4	3594.0
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	726.5	443.3	160.1	64.6	609.5	49.3	21.5	24.6	15.4	9.2	30.8	24.6	15.4	2194.8

D: Domestic; A: Agricultural; I: Industrial.

Table 4.9: (Continued).

Year	Sector	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2035	D	1185.1	991.8	292.7	151.4	575.8	207.5	77.2	121.0	42.0	44.5	65.3	159.3	72.1	3985.8
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	949.5	579.3	209.2	84.5	796.6	64.4	28.2	32.2	20.1	12.1	40.2	32.2	20.1	2868.5
2040	D	1321.3	1089.7	329.6	168.8	632.7	229.1	85.7	135.6	44.8	50.1	72.1	179.4	82.0	4420.7
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	1240.9	757.2	273.4	110.4	1041.1	84.1	36.8	42.1	26.3	15.8	52.6	42.1	26.3	3749.0
2045	D	1473.2	1197.2	371.1	188.2	695.1	252.9	95.1	151.9	47.8	56.4	79.6	202	93.2	4903.6
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	1621.8	989.6	357.3	144.3	1360.7	110.0	48.1	55.0	34.4	20.6	68.7	55.0	34.4	4899.8
2050	D	1642.5	1315.4	417.8	209.9	763.7	279.3	105.5	170.2	50.9	63.5	87.8	227.4	106.0	5439.8
	A	3467.0	737.0	775.0	1866.0	734.0	330.0	1099.0	565.0	100.0	6.0	1196.0	1712.0	207.0	12794.0
	I	2119.6	1293.3	467.0	188.6	1778.3	143.7	62.9	71.9	44.9	26.9	89.8	71.9	44.9	6403.8

D: Domestic; A: Agricultural; I: Industrial.

CHAPTER 5

RESULTS AND DISCUSSION

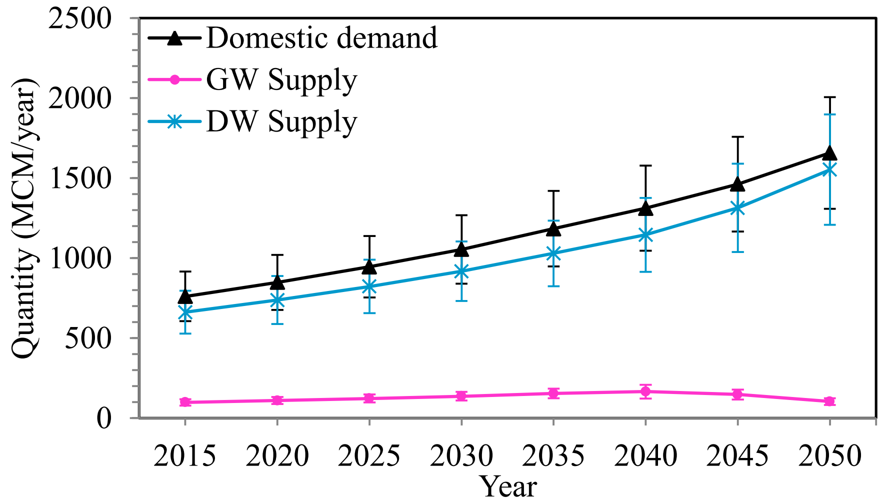
5.1 Introduction

The LINGO optimizer software [67] was applied for reasonable distributions of multiple water resources to multiple users in different regions of Saudi Arabia. The results for each region are discussed below.

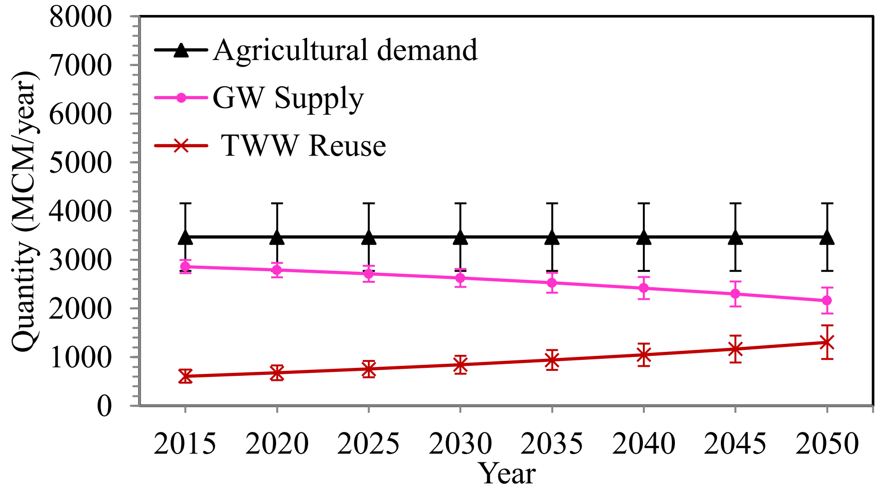
5.2 Riyadh Region

5.2.1 Sector Wise Water Demands Satisfaction

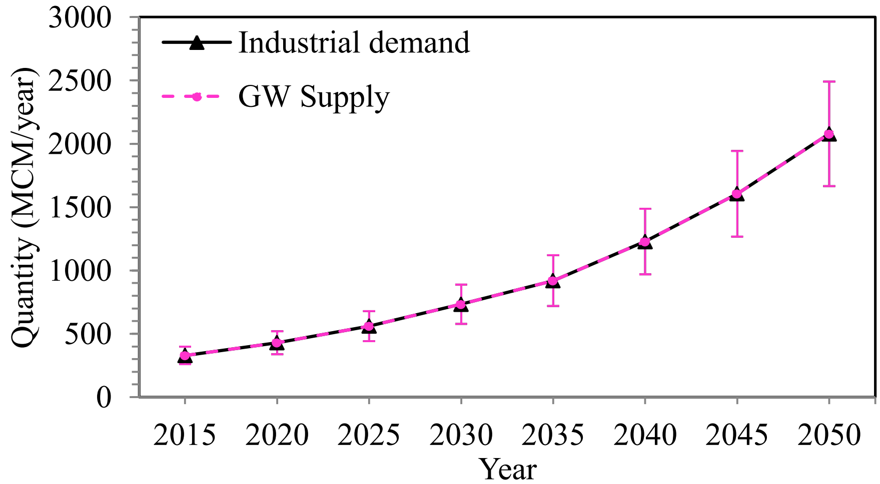
The priorities R_1, R_3 and R_5 were achieved, meaning that water demands in the domestic, agricultural and industrial sectors were satisfied. Figure 5.1 shows the sector wise water demands and the source wise water distributions for the period of 2015-2050. The domestic water demand in 2015 is 761.6 MCM, which may increase to 1658.1 MCM in 2050 (Figure 5.1a). The projected supplies in 2015 are 99.3 and 662.3 MCM of GW and DW respectively. In 2050, these supplies are predicted to be 104.5 and 1553.6 MCM of GW and DW respectively. The agricultural water demand is satisfied by GW and TWW. GW extraction is likely to be reduced from 2858.5 MCM in 2015 to 2162.1 MCM in 2050. TWW reuse for agriculture needs to be increased during this period (Figure 5.1b). Water demands in the industrial sector shows increasing trend. The industrial water demand may increase from 328.5 MCM in 2015 to 2119.6 MCM by 2050 (Figure 5.1c), which is fully satisfied by GW.



(a)



(b)



(c)

Figure 5.1: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Riyadh region: Mean (solid lines) and standard deviations (error bars).

The proportions of water supplies from multiple sources to multiple users in Riyadh region are presented in Table 5.1. GW contribution to domestic sector was approximately 13% for up to 2035, which was reduced to approximately 6.3% in 2050. Throughout these years, DW satisfies 87 to 93.7% of domestic water demands. The low contributions of GW in domestic sector can be explained by the higher levels of TDS in GW. GW has high level of TDS, which is blended with DW to have the TDS of 500 ppm or less. It is to be noted that satisfaction of domestic water demand will require additional supply of DW than the current levels, meaning that the supplies of DW have to be increased or alternative sources have to be developed. The contribution of GW to agriculture is expected to decrease by 20% (from 82.4 to 62.4%) from 2015 to 2050, while this reduction will be compensated by maximizing the reuse of TWW. In 2015, TWW contributes 17.6% of agricultural water demand, which will be increased to 37.6% in 2050. The water demands in the industrial sector from 2015 through 2050 will be satisfied by GW.

Table 5.1: Water supply contribution (%) from different sources to respective demand in Riyadh region.

Year	Domestic demand		Agricultural demand		Industrial demand
	GW	DW	GW	TWW	GW
2015	13	87	82.4	17.6	100
2020	13	87	80.4	19.6	100
2025	13	87	78.2	21.8	100
2030	13	87	75.7	24.3	100
2035	13	87	72.9	27.1	100
2040	12.6	87.4	69.8	30.2	100
2045	10.1	89.9	66.3	33.7	100
2050	6.3	93.7	62.4	37.6	100

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.2.2 Water Quality Satisfaction

The maximum allowable TDS in the domestic, agricultural and industrial sectors were 500, 3500 and 2000 ppm respectively. The priorities, R_2, R_4 and R_6 were achieved, indicating the achievement of target TDS for each sector. Table 5.2 summarizes the TDS for various demand sectors in 2015 through 2050. It can be noted that the TDS of blended water for domestic sector in 2015 - 2035 is equal to the maximum allowable level. In 2040, 2045 and 2050, the blended water may have the TDS of 484.4, 399.5 and 269 ppm, respectively, which can be explained by the higher proportions of DW in the blended water in these years. The TDS of water supplied from a single source for a specific purpose needs to be controlled at the supply source through treatment; therefore, it appears as is at the consumption sectors (e.g., agricultural and industrial water).

Table 5.2: Water quality achievement in terms of TDS (ppm) for various demand sectors in Riyadh region.

Year	Domestic sector	Agricultural sector		Industrial sector
	Blended water (GW+DW)	GW	TWW	GW
2015	500	3500	2000	300
2020	500	3500	2000	300
2025	500	3500	2000	300
2030	500	3500	2000	300
2035	500	3500	2000	300
2040	484.4	3500	2000	300
2045	399.5	3500	2000	300
2050	269.0	3500	2000	300

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.2.3 Source Wise Predicted Water Demands

Figure 5.2 shows the predicted quantities of GW, DW and TWW to be supplied to Riyadh region for the period of 2015-2050. GW supply increases with time. In 2015, GW extraction is 3286 MCM, which is likely to increase to 4345 MCM in 2050, indicating an increase of approximately 1.0% per year. In 2015, there is a need to supply 662 MCM of DW, which is 324 MCM more than the current supply of DW at this time. Further, DW supply needs to be increased to 1554 MCM by 2050. With the assumption of 662 MCM of DW in 2015, DW needs to be increased by 3.8% per year (Figure 5.2b). The predicted quantity of TWW was assumed to be equal to the generated wastewater, which needs to be ensured for maximizing TWW reuse for agricultural purposes. In 2015, needs of TWW reuse is 609 MCM, which is projected to increase to 1305 MCM in 2050 (3.3% increase per year). However, it is to be noted that currently, only a fraction of the generated wastewater is treated and a much smaller fraction of TWW is recycled for reuse.

In context to water availability, GW showed positive deviations in all years, meaning that the priority to maximize GW conservation (R_9) was achieved. The maximum withdrawal of GW is 4345 MCM in 2050, which satisfies the current rate of water extraction. Assuming the constant extraction of GW of 4369 MCM per year [21], this source satisfies the demands from 2015 through 2050 (Figure 5.2a). The current supply of DW is much lower than the predicted quantity in all years (Figure 5.2b), indicating that additional supply of DW is needed. To satisfy domestic water demands from 2015 through 2050 at the specified level of TDS, supply of DW needs to be increased to approximately 4.6 folds to the current level of DW supply. At present, supply of DW is approximately 338 MCM per year [21]. There is a need of approximately 662 MCM of DW in 2015 and 1554 MCM of DW in 2050. Increase in DW supply can be obtained gradually following the satisfaction DW demands in 2015. In case of TWW, current capacity of treatment plants is approximately 346 MCM per year [21], while generation of domestic wastewater in 2015 is approximately 609 MCM. In contrast, only 311 MCM/year of wastewater is being treated from which 80 MCM/year is recycled for reuse. There is a need to build infrastructure to collect and treat the domestic wastewater in full and recycle the TWW for agricultural reuse. In 2050, generation of domestic wastewater is estimated to be 1305 MCM, which needs to be fully treated and recycled to satisfy the agricultural water demands in this year (Figure 5.2c).

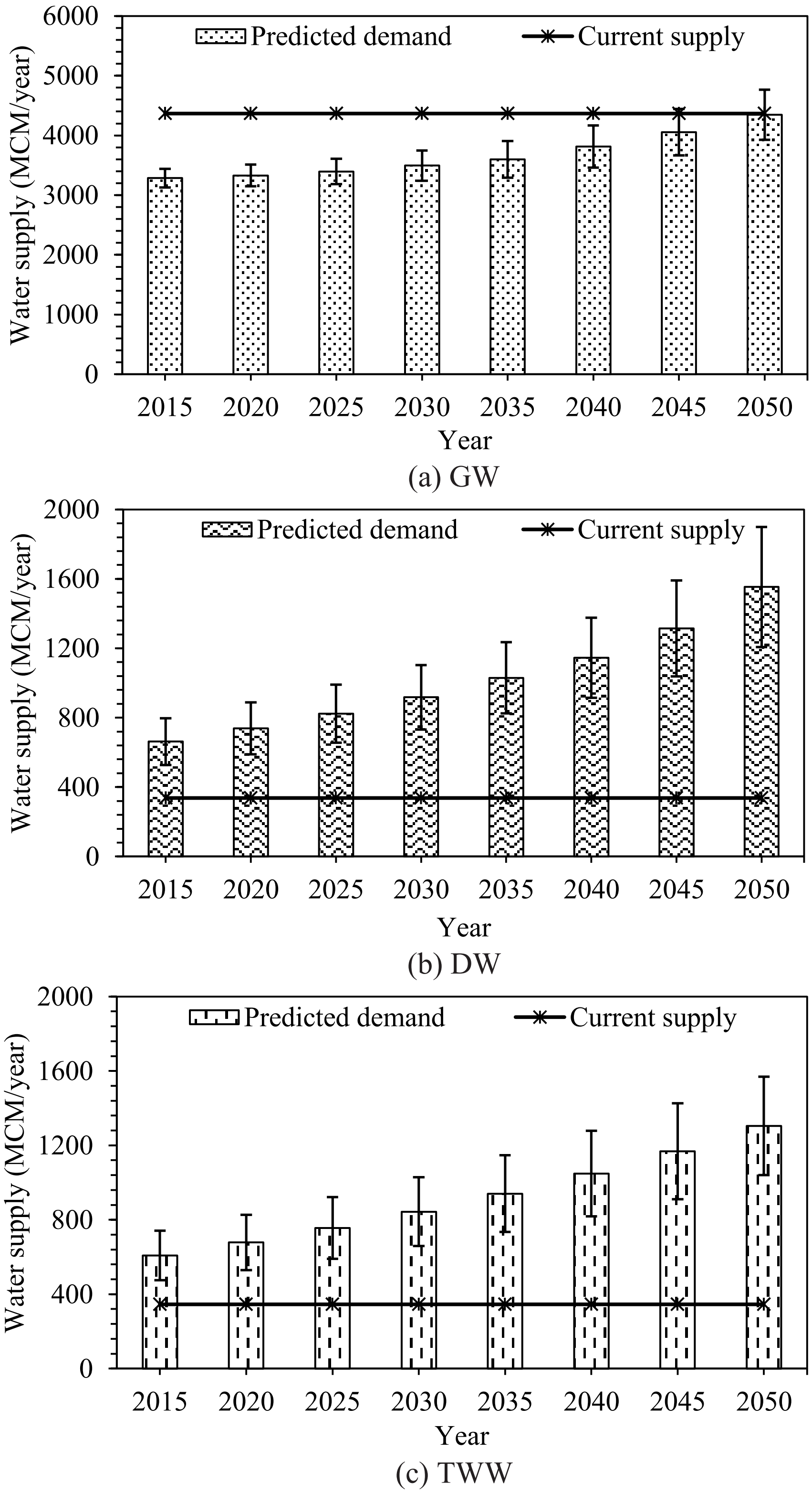


Figure 5.2: Predicted water demands from current supply sources in Riyadh region. Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of water are presented in Table 5.3. The results indicate that the current rate of GW extraction is likely to deliver the predicted quantities till 2035, while in 2040, 2045 and 2050, there will be 4%, 23% and 51% chances of non-satisfying the predicted quantities. The current rate of DW supply is not enough for satisfying the predicted amounts of DW in any year. The probabilities of satisfying the predicted quantity of TWW by the current capacity of TWW are 2% and 1% in 2015 and 2020 respectively. Beyond 2020, the current capacity of TWW cannot satisfy any of the 100 random scenarios assessed in this study (Table 5.3).

Table 5.3: Probabilities of satisfying the predicted water from current supply sources in Riyadh region (%).

Year \ Source	GW	DW	TWW
2015	100.0	0.0	2.0
2020	100.0	0.0	1.0
2025	100.0	0.0	0.0
2030	100.0	0.0	0.0
2035	100.0	0.0	0.0
2040	96.0	0.0	0.0
2045	77.0	0.0	0.0
2050	49.0	0.0	0.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.2.4 Cost of Water Supply

The costs of using water from different sources are shown in Figure 5.3. The costs of using predicted quantities of GW, DW and TWW in 2015 are approximately 6038.6, 4569.4 and 3263.3 million SR respectively. In 2050, these costs have been predicted to 7984.5, 10719.8 and 6997.5 million SR respectively. The cost for DW is likely to exceed the cost for GW starting from 2035, while the predicted quantity of GW is approximately 2.8 – 3.5 times to the predicted quantity of DW. This indicates that the development of alternative cost-effective source other than DW may lower the overall cost. Further, reduction of TDS in GW using the cost-effective technology prior to blending with the DW may increase the fractions of GW and thus lower the overall cost. The costs of TWW reuse may be increased from 3263.3 million SR in 2015 to 6997.5 million SR in 2050. The total cost of water from different sources has been estimated to be 13.9 billion SR in 2015, which may be increased to 25.7 billion SR in 2050. However, it is to be noted that the development of new desalination and/or wastewater treatment technologies in future may reduce the cost of DW and TWW.

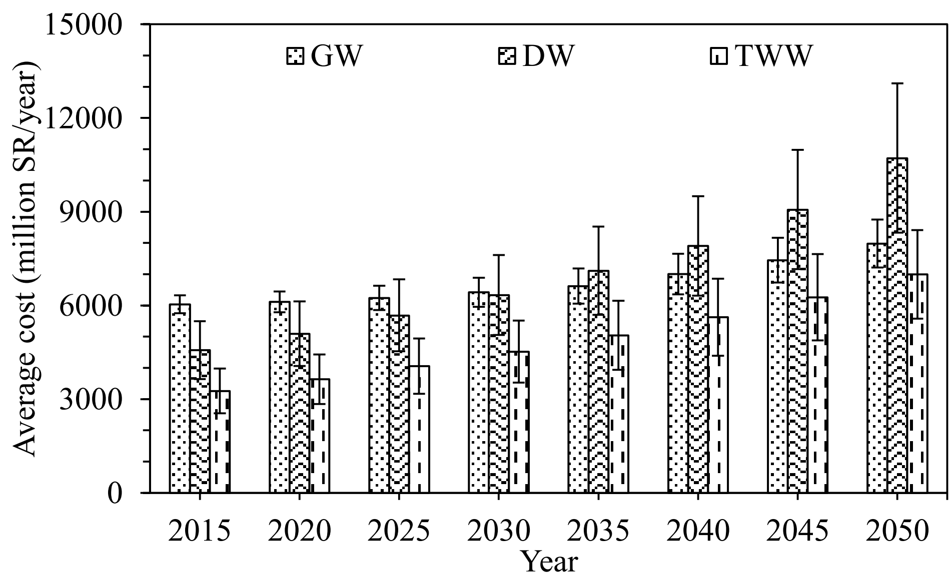


Figure 5.3: Average cost of supplying the predicted quantities of water from different sources in Riyadh region: Mean (bars) and standard deviation (error bars).

5.3 Makkah Region

5.3.1 Sector Wise Water Demands Satisfaction

Water demands in domestic, agricultural and industrial sectors were successfully satisfied. Figure 5.4 shows the source wise necessary distributions for satisfying sector wise water demands for the period from 2015 to 2050 in Makkah region. During this period, domestic water demand is projected to increase from 676 in 2015 to 1306.3 MCM in 2050, which is satisfied by GW, SW and DW (Figure 5.4a). GW distribution to domestic sector increases from 83.1 MCM in 2015 to 120.5 MCM in 2035; thereafter this distribution is forecasted to reduce gradually to 3 MCM in 2050. The withdrawal of SW to domestic sector shows fluctuation. It is likely to increase from 38.8 MCM in 2015 to 43.6 MCM in 2025, then it shows a decreasing trend till 2040 (38.0 MCM) and again increases to 40.3 MCM by 2050. DW supply to domestic sector is expected to increase from 554.1 MCM in 2015 to 1262.9 MCM in 2050. The agricultural water demand of 737 MCM/year is satisfied by GW, SW and TWW. GW extraction to agricultural sector is likely to reduce from 193.9 MCM in 2015 to 4.2 MCM in 2050. The expected supply of SW for agricultural uses decreases from 5 MCM in 2015 to 0.2 in 2025 while in 2040 and 2050; these may be 5.8 and 3.5 MCM respectively. TWW reuse for agriculture needs to be increased from 538.1 MCM in 2015 to 729.3 MCM in 2050 (Figure 5.4b). The industrial water demand has been forecasted to increase from 200.5 MCM in 2015 to 1311.9 MCM by 2050 (Figure 5.4c).

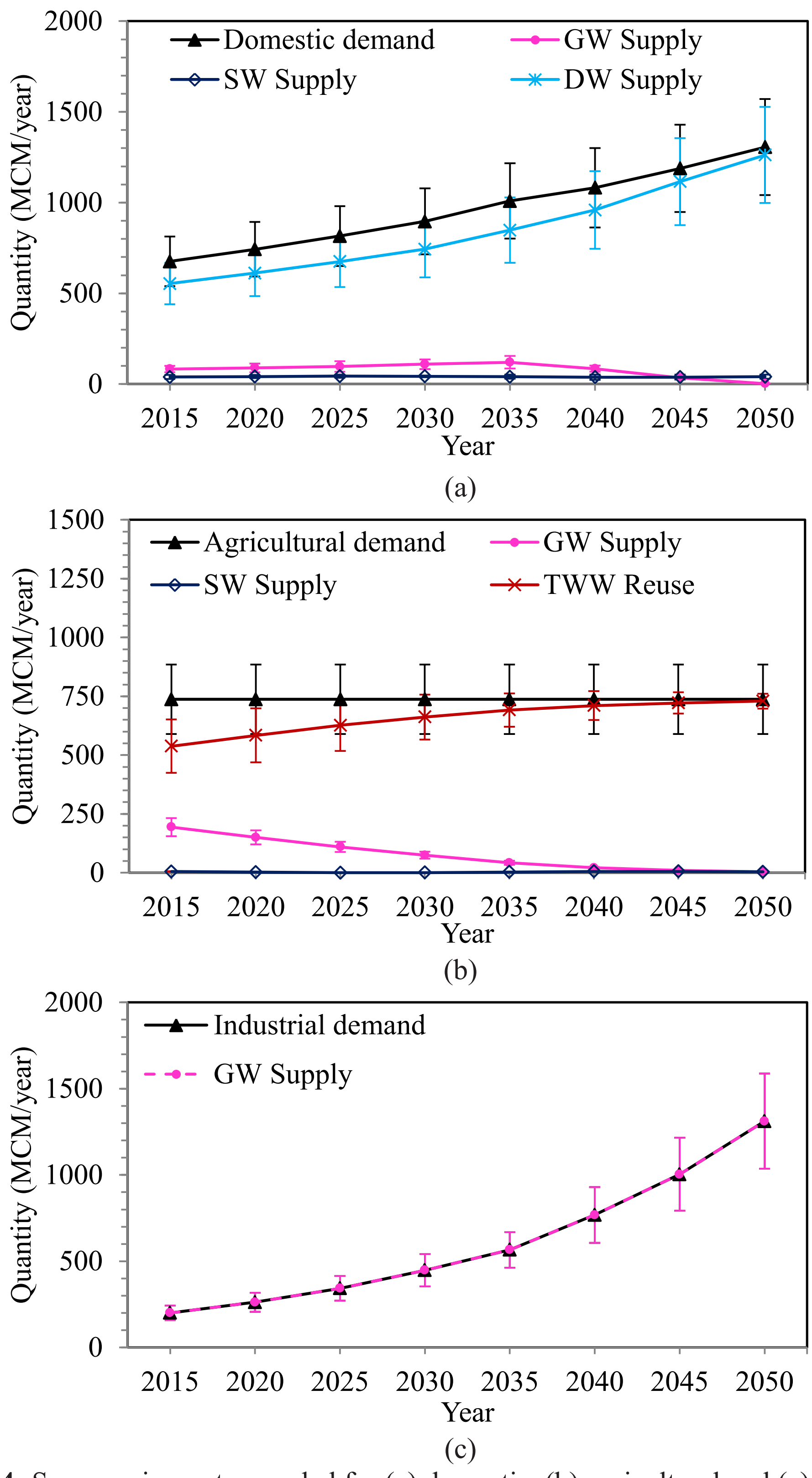


Figure 5.4: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Makkah region: Mean (solid lines) and standard deviations (error bars).

The water contributions (percent) are shown in Table 5.4. The proportion of GW supply to domestic sector in 2015-2035 was approximately 12.3, 11.9, 11.8, 12.2 and 11.8%, respectively, which was reduced to approximately 7.9, 2.9 and 0.2% in 2040, 2045 and 2050, respectively. During these years, SW and DW satisfy 3.2 - 5.8 and 81.9 - 96.6 % of domestic water demands, respectively. The contribution of GW to agriculture sector from 2015 to 2050 is expected to decrease from 26.3 to 0.5% (25.8%), while this reduction will be compensated by maximizing SW and reuse of TWW. GW fully satisfies the water demands in the industrial sector from 2015 through 2050.

Table 5.4: Water supply contribution (%) from different sources to respective demand in Makkah region.

Year	Domestic sector			Agricultural sector			Industrial sector
	GW	SW	DW	GW	SW	TWW	GW
2015	12.3	5.8	81.9	26.3	0.7	73	100
2020	11.9	5.7	82.2	20.4	0.3	79.3	100
2025	11.8	5.6	82.6	14.9	0.03	85	100
2030	12.2	5	82.8	10.1	0.1	89.8	100
2035	11.8	4.2	84	5.7	0.5	93.8	100
2040	7.9	3.6	88.5	2.9	0.8	96.3	100
2045	2.9	3.4	93.7	1.4	0.7	97.9	100
2050	0.2	3.2	96.6	0.5	0.5	99	100

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater.

5.3.2 Water Quality Satisfaction

Table 5.5 shows the TDS for different sectors from 2015 through 2050. The priorities R_2, R_4 and R_6 were achieved, meaning that the desired TDS for each sector was satisfied. It is to be noted that the TDS of blended water for domestic sector may reduce from 499.8 ppm in 2015 to 58.6 ppm in 2050.

Table 5.5: Water quality achievement in terms of TDS (ppm) for various demand sectors in Makkah region.

Year	Domestic sector		Agricultural sector			Industrial sector
	Blended water (GW + DW)	SW	GW	SW	TWW	GW
2015	499.8	225	3500	225	2000	300
2020	486.8	225	3500	225	2000	300
2025	479.1	225	3500	225	2000	300
2030	491.7	225	3500	225	2000	300
2035	475.3	225	3500	225	2000	300
2040	333.5	225	3500	225	2000	300
2045	153.1	225	3500	225	2000	300
2050	58.6	225	3500	225	2000	300

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater.

5.3.3 Source Wise Predicted Water Demands

The predicted water supplies are shown in Figure 5.5. Supply of GW shows increasing trend with time (approximately 5% per year). The extraction of GW is 477.4 MCM in 2015, which is expected to increase to 1319.1 MCM in 2050 (Figure 5.5a). The SW was fully allocated to domestic and agricultural sectors (Figure 5.5b). DW supply needs to be increased by approximately 3.7% per year. In 2015, about 554.1 MCM of DW is needed to supply, which is expected to be increased to 1262.9 MCM by 2050 (Figure 5.5c). To ensure maximizing TWW reuse for agricultural purposes, the predicted quantity of TWW was assumed to be equal to the generated wastewater. In 2015, the predicted TWW to be reused for agricultural purposes is 538.1 MCM, which is likely to increase to 729.3 MCM in 2050. (Figure 5.5d).

In regards to water availability, GW withdrawal was assumed to be 911 MCM/year [21]. This rate is satisfactory for up to 2040. In 2045 and 2050, the predicted GW shows a positive deviation above the current extraction of GW of approximately 81 and 408.1 MCM, respectively, indicating the non-achievement of minimizing GW extraction in these years (Figure 5.5a). In the event of non-availability of additional GW, the demand needs to be satisfied through the other sources, such as, increasing the supplies of DW, development of additional SW sources and harvesting rainwater and/or applying water conservation techniques. In case of DW, the current supply is approximately 613 MCM per year [21]. The years 2015 and 2020 demonstrate the achievement of the tenth priority (R_{10}) to minimize the overproduction of DW, where the DW supply meets the predicted quantity. However, there is a need of approximately 62.3 MCM of additional DW in 2025, which is forecasted to be 649.9 MCM in 2050 (Figure 5.5c). Regarding TWW, the current capacity of treatment plants is approximately 357 MCM per year [21], while generation of domestic wastewater in 2015 is approximately 538.1 MCM, which is estimated to increase to 729.3 MCM by 2050 (Figure 5.5d). The data showed that only 216 MCM/year of generated wastewater is treated, while small fraction (around 34.8 MCM/year) is reused [21]. The generated wastewater needs to be fully treated and recycled for agricultural uses.

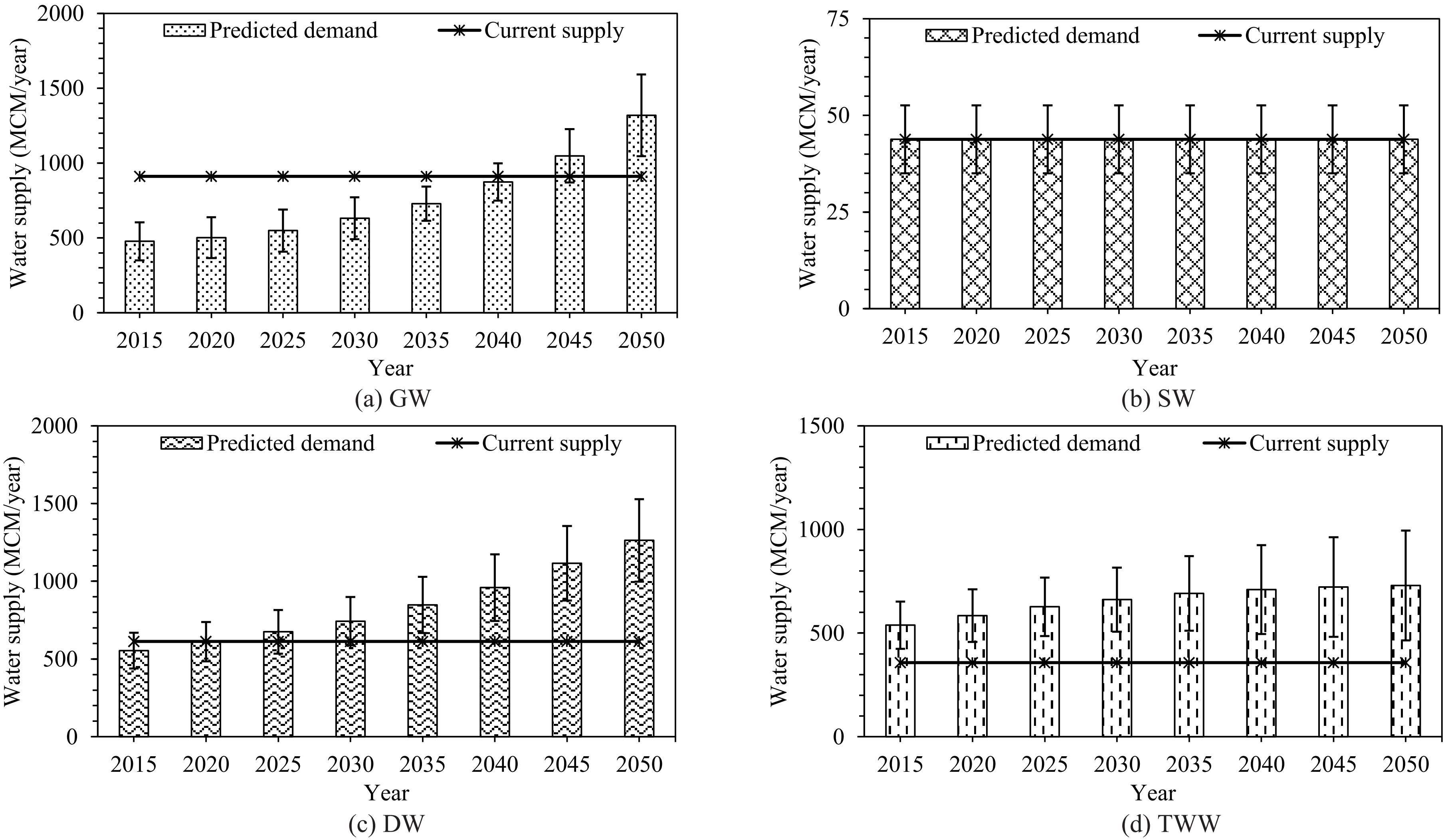


Figure 5.5: Predicted water demands from current supply sources in Makkah region. Error bars represent the standard deviations.

Table 5.6 summarizes the probabilities of satisfying the predicted quantity of water from current supplies. Current rate of GW extraction is likely to satisfy the predicted quantities from 2015 through 2025. Starting from 2030, probabilities of satisfaction will be reduced (Table 5.6). The SW shows the full satisfaction of the predicted quantity. In 2015, chance of not satisfying the predicted DW is 28%, which will reach to 100% by 2050. The probabilities of satisfying the predicted quantity of TWW by the current sewage capacity are 6%, 3% and 1% in 2015, 2020 and 2025, respectively.

Table 5.6: Probabilities of satisfying the predicted water from current supply sources in Makkah region (%).

Year \ Source	GW	SW	DW	TWW
2015	100.0	100.0	72.0	6.0
2020	100.0	100.0	54.0	3.0
2025	100.0	100.0	27.0	1.0
2030	99.0	100.0	19.0	0.0
2035	96.0	100.0	12.0	0.0
2040	60.0	100.0	4.0	0.0
2045	24.0	100.0	3.0	0.0
2050	4.0	100.0	0.0	0.0

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater.

5.3.4 Cost of Water Supply

Figure 5.6 shows the costs of using water from different sources. Cost of using GW may be increased from 877.1 million SR in 2015 to 2423.6 million SR in 2050. The cost of supplying SW is 80.6 million SR per year. The annual increase of cost for supplying DW is approximately 3.7% per year. In 2015, DW may cost 3823.5 million SR, which is estimated to be 8714.3 million SR in 2050. The costs of TWW reuse may be increased from 2885.6 million SR in 2015 to 3910.9 million SR in 2050. The cost for DW is always exceeding the cost for supplying water from other sources. The total cost of water from different sources has been estimated to be 7.7 billion SR in 2015, which may be increased to 15.1 billion SR in 2050.

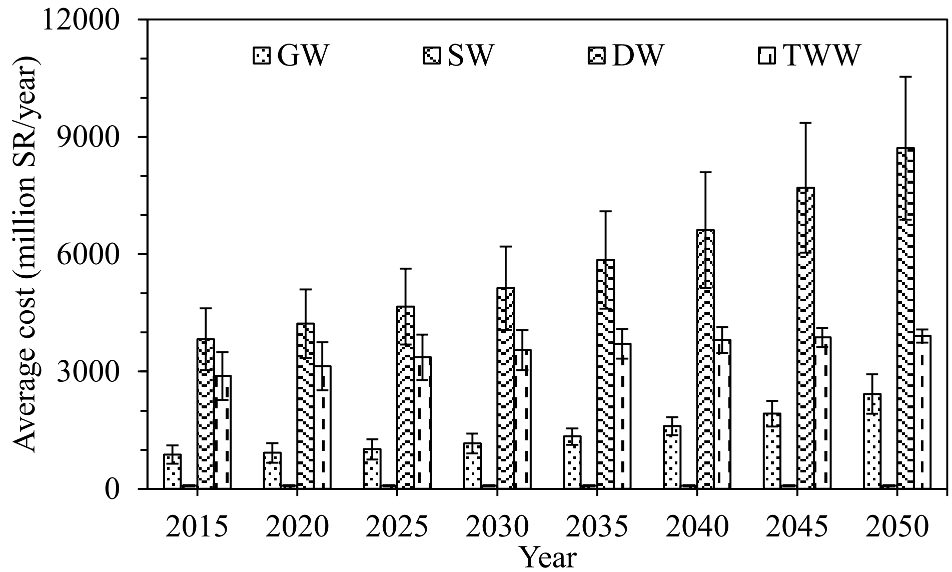


Figure 5.6: Average cost of supplying the predicted quantities of water from different sources in Makkah region: Mean (bars) and standard deviation (error bars).

5.4 Madinah Region

5.4.1 Sector Wise Water Demands Satisfaction

Figure 5.7 shows the satisfaction of sector wise water demands. Figure 5.7a indicates that the domestic water demand in 2015 is 187.5 MCM, which is satisfied by 24.4 MCM of GW and 163.1 MCM of DW. In 2050, distribution of GW and DW is estimated to be 32.5 and 382.4 MCM respectively. For agriculture, GW extraction will be reduced from 630.4 MCM in 2015 to 443.5 MCM in 2050, indicating an average reduction of approximately 0.8% per year (Figure 5.7b). TWW reuse in agricultural sector needs to be maximized from 144.6 MCM in 2015 to 331.5 MCM in 2050 (Figure 5.7b). The industrial water demand is predicted to increase from 72.4 MCM in 2015 to 472.9 MCM by 2050, which is satisfied by GW (Figure 5.7c).

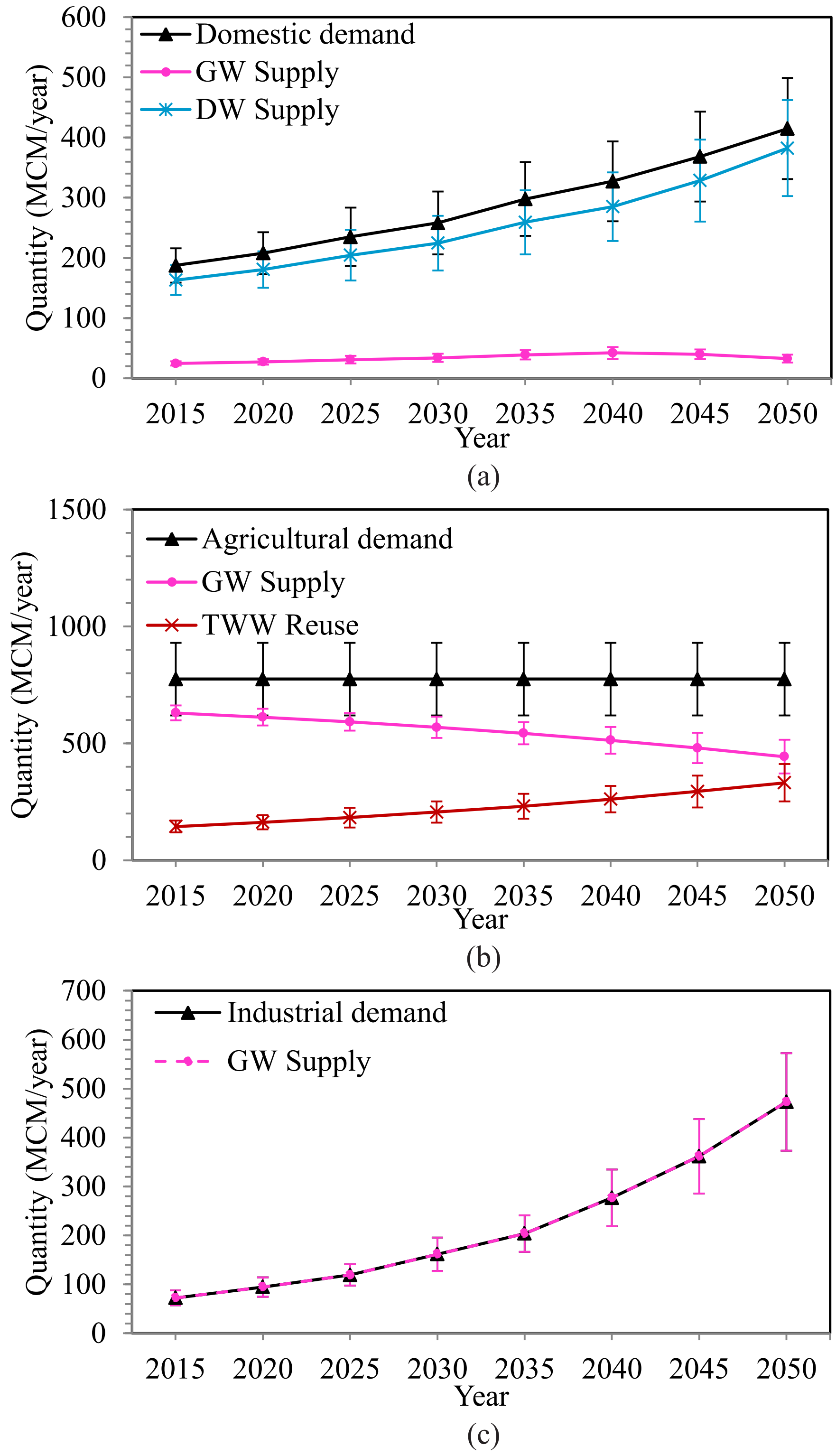


Figure 5.7: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Madinah region: Mean (solid lines) and standard deviations (error bars).

Table 5.7 details the percentages of water contribution from various sources to the consumption sectors. GW contribution to domestic sector was approximately 13% in 2015 through 2035, which may be reduced to approximately 12.8%, 10.8% and 7.7 in 2040, 2045 and 2050 respectively. Throughout these years, DW satisfies 87 to 92.3% of domestic water demands. The contribution of GW to agriculture sector is estimated to reduce from 81.3% in 2015 to 57.2 % in 2050 (24.1% reduction). TWW needs to satisfy 18.7% of agricultural water demand in 2015, and it is likely to be increased to 42.8% by 2050. The water demand in the industrial sector from 2015 through 2050 is fully satisfied by GW.

Table 5.7: Water supply contribution (%) from different sources to respective demand in Madinah region.

Year	Domestic sector		Agricultural sector		Industrial sector
	GW	DW	GW	TWW	GW
2015	13.0	87.0	81.3	18.7	100.0
2020	13.0	87.0	79.0	21.0	100.0
2025	13.0	87.0	76.4	23.6	100.0
2030	13.0	87.0	73.4	26.6	100.0
2035	13.0	87.0	70.1	29.9	100.0
2040	12.8	87.2	66.2	33.8	100.0
2045	10.8	89.2	62.0	38.0	100.0
2050	7.7	92.3	57.2	42.8	100.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.4.2 Water Quality Satisfaction

The TDS levels for various sectors from 2015 through 2050 are shown in Table 5.8. The TDS of blended water for domestic sector is equal to the maximum allowable level in 2015-2035. In 2040, 2045 and 2050, the blended water may have the TDS of 491.4, 422.2 and 316.7 ppm respectively.

Table 5.8: Water quality achievement in terms of TDS (ppm) for various demand sectors in Madinah region.

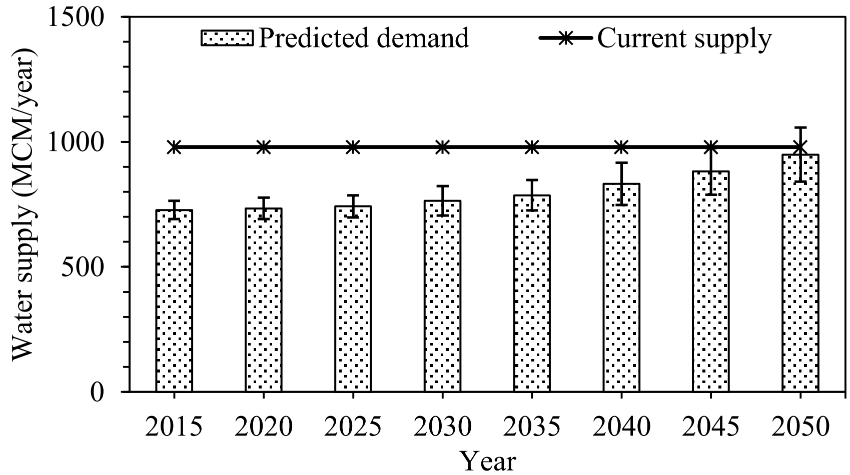
Year	Domestic sector	Agricultural sector		Industrial sector
	Blended water (GW + DW)	GW	TWW	GW
2015	500	3500	2000	300
2020	500	3500	2000	300
2025	500	3500	2000	300
2030	500	3500	2000	300
2035	500	3500	2000	300
2040	491.4	3500	2000	300
2045	422.2	3500	2000	300
2050	316.7	3500	2000	300

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

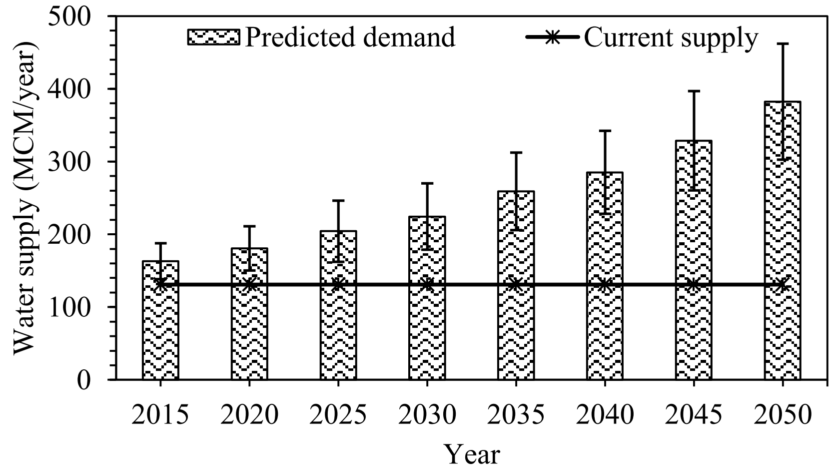
5.4.3 Source Wise Predicted Water Demands

Figure 5.8 displays the predicted amounts of water to be supplied from GW, DW and TWW. In 2015, water supplies are 727.2, 163.1 and 144.6 MCM of GW, DW and TWW respectively, which is projected to increase to 948.9, 382.4 and 331.5 MCM respectively by 2050. Supply of DW and TWW needs to be increased to approximately 2.3 folds to the water in 2015 respectively (Figure 5.8b, c), while GW is likely to be increased by approximately 0.9% per year (Figure 5.8a).

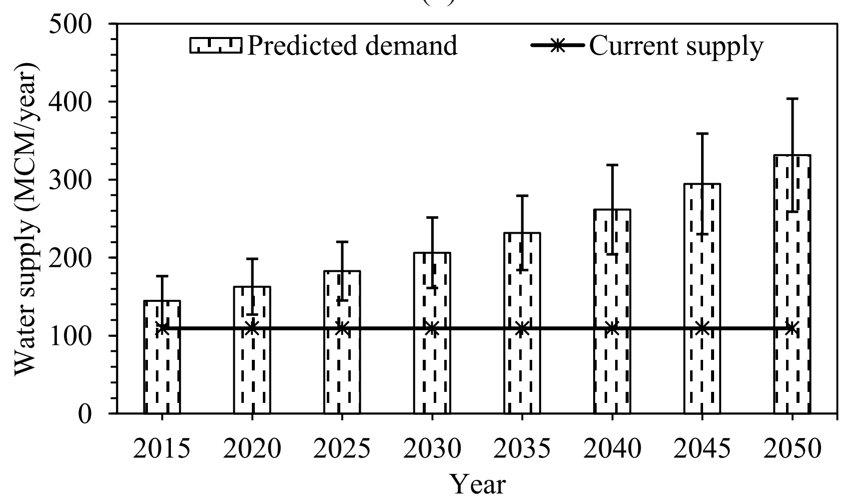
The current extraction rate of GW showed positive deviations, meaning that the objective to maximize GW conservation was achieved. The maximum extraction of GW is 948.9 MCM in 2050, which can be satisfied by the current rate of GW withdrawal. Assuming the constant supply of GW of 979 MCM per year [21], this source satisfies the demands from 2015 through 2050 (Figure 5.8a). However, additional DW is needed in all the years. Currently, supply of DW is approximately 131 MCM per year [21]. To satisfy domestic water demands from 2015 through 2050, there is a need of additional 32.1 MCM of DW in 2015 and 251.4 MCM of DW in 2050. The current capacity of wastewater plants is approximately 109.5 MCM per year [21], while generation of domestic wastewater in 2015 is approximately 144.6 MCM and it is expected to be 331.5 MCM in 2050 (Figure 5.8c). On the other side, only 87.6 MCM/year of generated wastewater is being treated [21]. Reuse of TWW in agricultural sectors needs to be maximized. Consequently, building infrastructures to collect and treat the domestic wastewater is needed in order to maximize TWW for agricultural reuse.



(a) GW



(b) DW



(c) TWW

Figure 5.8: Predicted water demands from current supply sources in Madinah region.

Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of GW, DW and TWW are shown in Table 5.9. The current rate of GW withdrawal is likely to deliver the predicted quantities till 2035, while in 2040, 2045 and 2050, there will be 1%, 27% and 40% chances of non-satisfying the predicted quantities in full respectively. The chance for satisfying the predicted DW in full is 7% and 3% in 2015 and 2020 respectively. Beyond 2020, the current supply of DW cannot satisfy the predicted quantity in any year. The existing wastewater plants may satisfy TWW demands in 14%, 7%, 2% and 1% cases in 2015, 2020, 2025 and 2030 respectively. Beyond 2030, the current capacity of these plants cannot fully satisfy any of the 100 random scenarios assessed in this study.

Table 5.9: Probabilities of satisfying the predicted water from current supply sources in Madinah region (%).

Year \ Source	GW	DW	TWW
2015	100.0	7.0	14.0
2020	100.0	3.0	7.0
2025	100.0	0.0	2.0
2030	100.0	0.0	1.0
2035	100.0	0.0	0.0
2040	99.0	0.0	0.0
2045	83.0	0.0	0.0
2050	60.0	0.0	0.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.4.4 Cost of Water Supply

The average costs of using water from different sources are presented in Figure 5.9. The costs of using GW, DW and TWW in 2015 are approximately 1336.1, 1125.4 and 775.5 million SR respectively. In 2050, these costs have been estimated to be 1743.4, 2638.5 and 1777.5 million SR, respectively. Among three supply sources, GW has the dominance of higher cost in 2015 and 2020, while from 2025 the cost for using DW is likely to exceed the cost for using GW. The total cost of using water from different sources has been estimated to be 3.2 billion SR in 2015, which is predicted to be 6.2 billion SR in 2050.

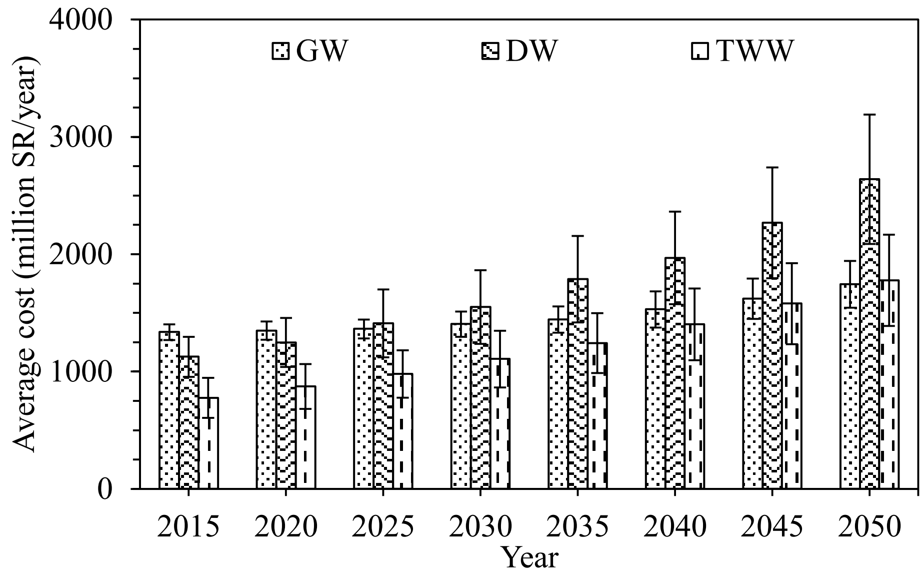


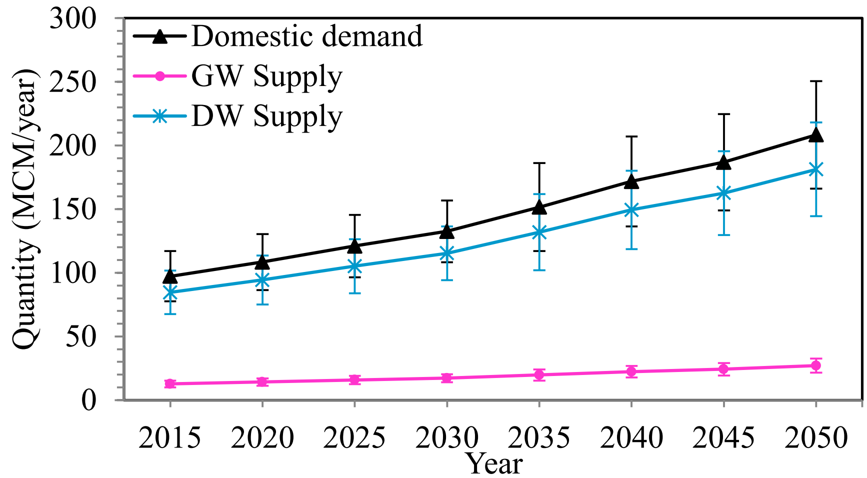
Figure 5.9: Average cost of supplying the predicted quantities of water from different sources in Madinah region: Mean (bars) and standard deviation (error bars).

5.5 Qaseem Region

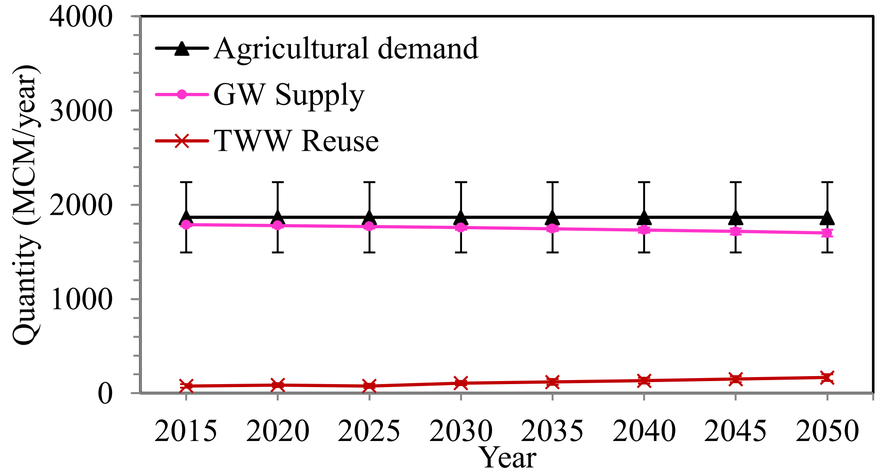
5.5.1 Sector Wise Water Demands Satisfaction

Water demands in the domestic, agricultural and industrial sectors were satisfied. Figure 5.10 shows the sector wise water demands and source wise water withdrawals needed to satisfy the demands for the period of 2015 through 2050. The domestic water demand in 2015 is 97.3 MCM, which is predicted to be 208.4 MCM in 2050 (Figure 5.10a). In 2015, the projected supplies of GW and DW to domestic sector are 12.7 and

84.6 MCM respectively. In 2050, these supplies have been forecasted to be 27.1 and 181.3 MCM respectively. Water demand for agriculture is 1866 MCM/year. From 2015-2050, GW supply for agriculture is likely to reduce from 1788.2 to 1699.5 MCM, while TWW reuse may be increased from 77.8 to 166.5 MCM, indicating approximately 3.3% increase per year (Figure 5.10b). The industrial water demand has been forecasted to increase from 29.3 MCM in 2015 to 185.3 MCM in 2050, which is fully satisfied by GW (Figure 5.10c).



(a)



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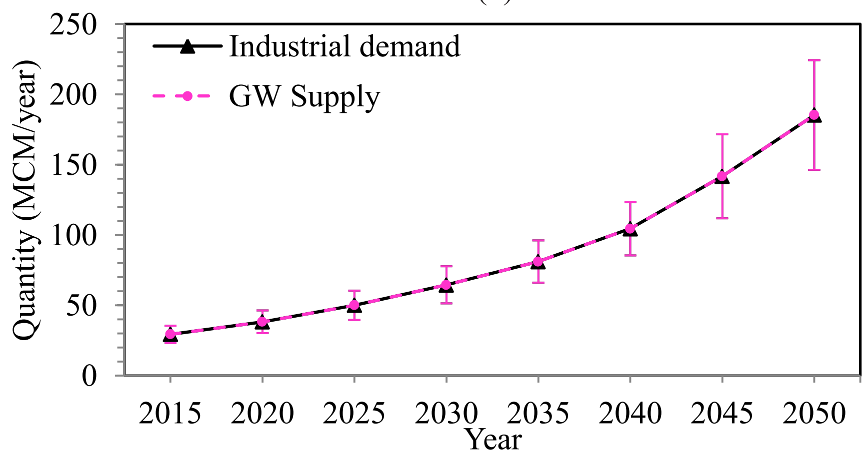


(c)

Figure 5.10: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Qaseem region: Mean (solid lines) and standard deviations (error bars).

The proportions of water supplies from multiple sources to multiple sectors are presented in Table 5.10. From 2015 through 2050, GW contribution to domestic sector was approximately 13%, whereas DW satisfies 87% of domestic water demands. Additional supply of DW is needed to satisfy the domestic water demands, which can be achieved through increasing DW supplies. Between 2015 and 2050, GW contribution to agriculture is expected to decrease from 95.8% to 91.1 %. During this period, contribution of TWW reuse may increase form 4.2% to 8.9%. Water demands in the industrial sector will be satisfied by GW.

Table 5.10: Water supply contribution (%) from different sources to respective demand in Qaseem region.

Year	Domestic sector		Agricultural sector		Industrial sector
	GW	DW	GW	TWW	GW
2015	13.0	87.0	95.8	4.2	100.0
2020	13.0	87.0	95.4	4.6	100.0
2025	13.0	87.0	94.8	5.2	100.0
2030	13.0	87.0	94.2	5.8	100.0
2035	13.0	87.0	93.6	6.4	100.0
2040	13.0	87.0	92.8	7.2	100.0
2045	13.0	87.0	92.0	8.0	100.0
2050	13.0	87.0	91.1	8.9	100.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.5.2 Water Quality Satisfaction

Table 5.11 summarizes the achievements of TDS for various sectors. It can be noted that the TDS of blended water for domestic sector is getting equal to the maximum allowable level.

Table 5.11: Water quality achievement in terms of TDS (ppm) for various demand sectors in Qaseem region.

Year	Domestic sector	Agricultural sector		Industrial sector
	Blended water (GW + DW)	GW	TWW	GW
2015	500	3500	2000	300
2020	500	3500	2000	300
2025	500	3500	2000	300
2030	500	3500	2000	300
2035	500	3500	2000	300
2040	500	3500	2000	300
2045	500	3500	2000	300
2050	500	3500	2000	300

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.5.3 Source Wise Predicted Water Demands

Figure 5.11 depicts the predicted quantities of water to be supplied from different sources. In 2015, the predicted quantity of GW, DW and TWW is 1830.2, 84.6 and 77.8 MCM respectively, which is expected to be 1911.9, 181.3 and 166.5 MCM in 2050 respectively. In 2015, GW satisfies approximately 91.8% of the total water demands, which is projected to be approximately 84.6% in 2050, indicating a reduction of 7.2%. Further, about 97.7% of predicted GW in 2015 is likely to be allocated to agricultural sectors, which is predicted to be 88.9% in 2050.

In case of water availability, current extraction of GW is 2190.7 MCM/year [21], which is likely to satisfy the demands for GW for 2015-2050. The current supply of DW is 8 MCM/year [21], which is much lower than the predicted quantity in all years (Figure 5.11b). To meet the domestic water demand in 2015, supply of DW needs to be increased to approximately 10.6 folds of the current level, while in 2050 this will be approximately

22.7 folds of the present supply. With the assumption of these quantities, there is additional need of approximately 76.6 and 173.3 MCM of DW in 2015 and 2050 respectively. Increase in DW to such a level might not be an easy task. As such, advanced treatment techniques can be employed to improve the finished GW quality, which may reduce the amounts of DW requirements. In context to TWW, the current capacity of wastewater plants is approximately 52.6 MCM per year [21], while generation of domestic wastewater in 2015 and 2050 is approximately 77.8 and 166.5 MCM respectively (Figure 5.11c). In contrast, only 44.7 MCM/year of wastewater is treated, from which about 13.4 MCM/year of TWW is recycled for reuse [21].

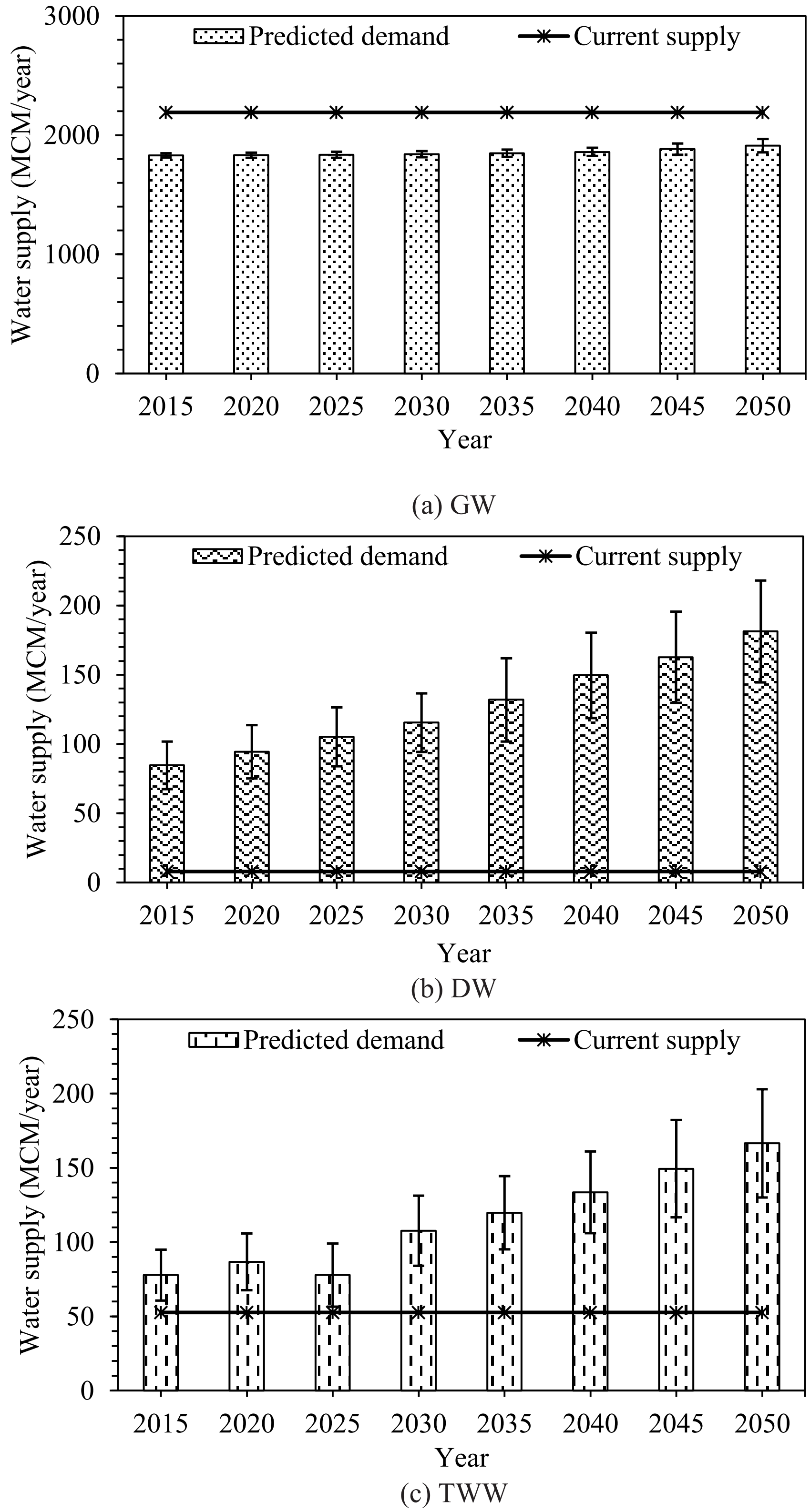


Figure 5.11: Predicted water demands from current supply sources in Qaseem region.

Error bars represent the standard deviations.

Table 5.12 summarizes the probabilities of satisfying the predicted quantities of water from different sources. The results indicate that the current rate of GW extraction is likely to deliver the predicted quantities from 2015-2050. The current rate of DW supply is not adequate to satisfy the predicted amounts of DW in any year. The probabilities of satisfying the predicted quantity of TWW by the current sewage capacity are 7%, 3% and 1% in 2015, 2020 and 2025 respectively.

Table 5.12: Probabilities of satisfying the predicted water from current supply sources in Qaseem region (%).

Year \ Source	GW	DW	TWW
2015	100.0	0.0	7.0
2020	100.0	0.0	3.0
2025	100.0	0.0	1.0
2030	100.0	0.0	0.0
2035	100.0	0.0	0.0
2040	100.0	0.0	0.0
2045	100.0	0.0	0.0
2050	100.0	0.0	0.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.5.4 Cost of Water Supply

The costs of using water from different sources are shown in Figure 5.12. In 2015, the cost of using predicted quantity of GW, DW and TWW is 3363, 583.9 and 417 million SR respectively. In 2050, these costs have been estimated to be 3513, 1251.4 and 893.3 million SR respectively. The cost of using GW is likely exceeding the cost for supplying DW and TWW in all years. The total cost of using water from various sources has been estimated to be 4.4 billion SR in 2050, which is predicted to be 5.7 billion SR in 2050 (approximately 0.8% increase annually). It is to be noted that, during the period of 2015 through 2050, about 62.1 – 77.1 % of the total cost is attributed by GW supply.

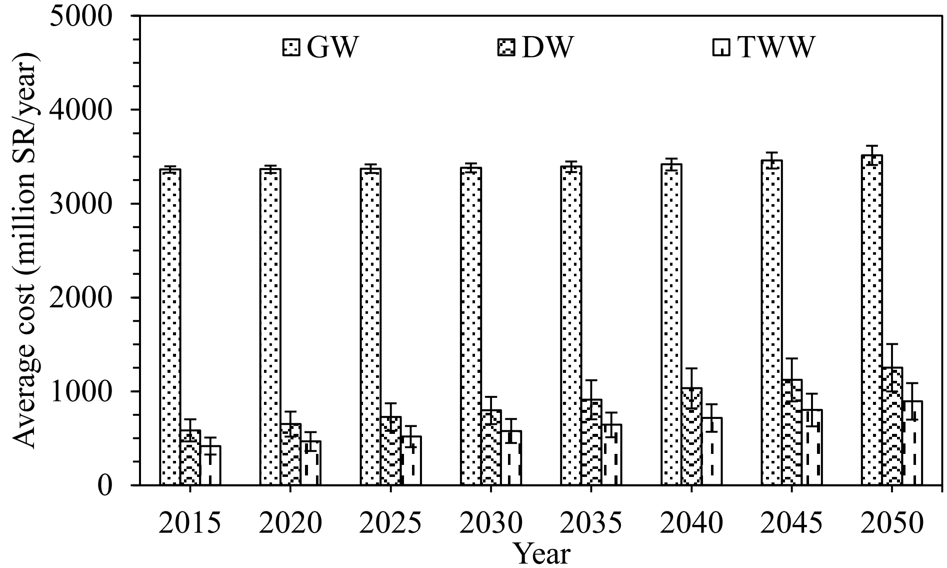
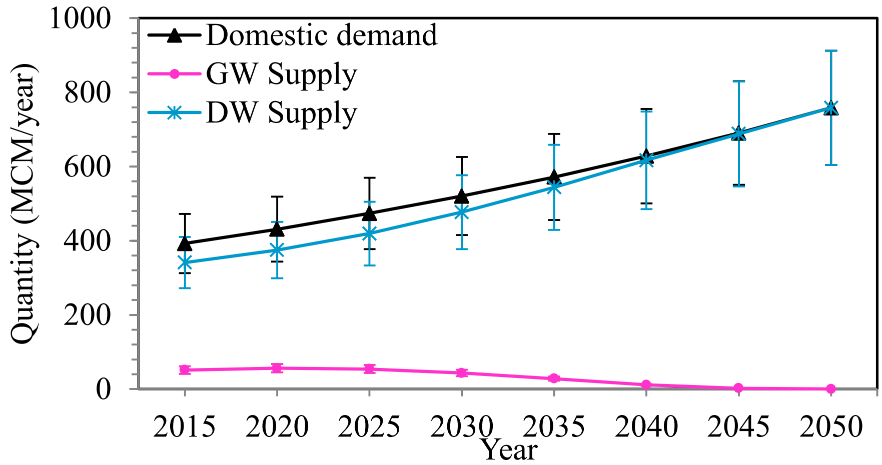


Figure 5.12: Average cost of supplying the predicted quantities of water from different sources in Qaseem region: Mean (bars) and standard deviation (error bars).

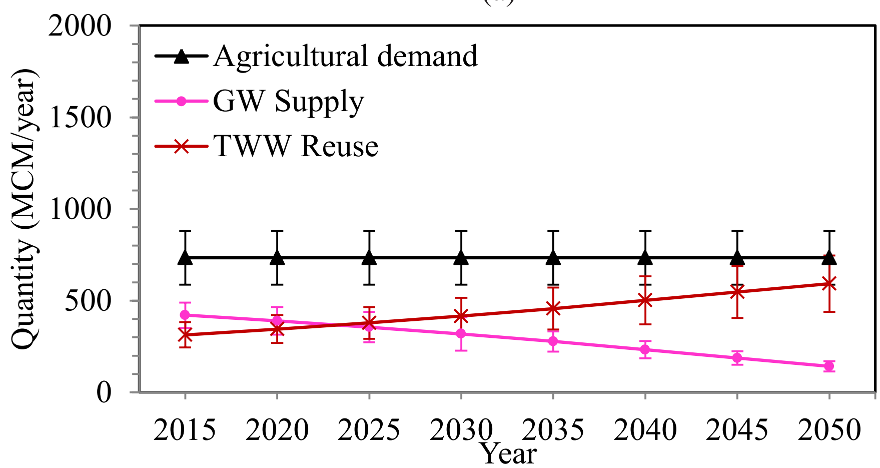
5.6 Eastern Region

5.6.1 Sector Wise Water Demands Satisfaction

The water demands in domestic, agricultural and industrial sectors were satisfied through supplying water from different sources (Figure 5.13). From 2015 through 2050, the domestic water demand may increase from 392.5 MCM to 758.4 MCM, indicating an increase of approximately 365.9 MCM (Figure 5.13a). The projected extraction of GW for domestic purpose may be increased from 51.2 MCM in 2015 to 56.2 MCM in 2020, which is likely to decrease gradually to 2 MCM in 2045. In 2050, the domestic sector may not receive water from GW source. In case of DW, approximately 341.3 MCM may be delivered for domestic purposes in 2015, while in 2050; about 758.4 MCM of DW is expected to fully satisfy domestic water demands (Figure 5.13a). The agricultural water demand of 734 MCM/year is satisfied by GW and TWW (Figure 5.13b). GW supply for agriculture is likely to be reduced from 420.4 MCM in 2015 to 141.3 MCM in 2050 (approximately 1.9% decrease per year). Reuse of TWW in agricultural sector is estimated to increase from 313.6 MCM in 2015 to 592.7 MCM by 2050. The industrial water demand is fully satisfied by GW, which shows increasing trend (Figure 5.13c).



(a)



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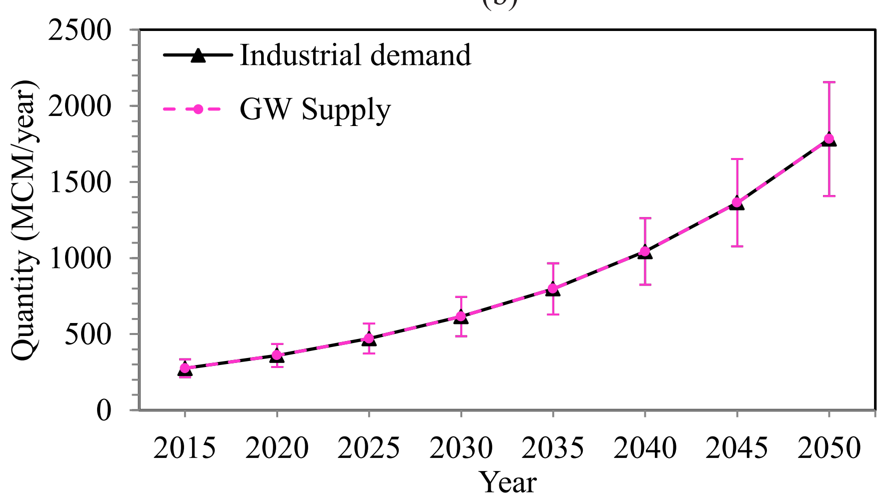


(c)

Figure 5.13: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Eastern region: Mean (solid line) and standard deviations (error bars).

Table 5.13 illustrates the proportions of water supplies from multiple sources to multiple users. GW contribution to domestic sector was approximately 13% in 2015 and 2020, which was reduced to approximately 0.3% in 2045. Throughout these years, DW satisfies 87 to 99.7% of domestic water demands. In 2050, domestic water demand is fully satisfied by DW. From 2015 to 2050, contribution of GW to agriculture sector is expected to decrease from 57.3% to 19.3%. Water demands in industrial sector will be satisfied by GW in all years.

Table 5.13: Water supply contribution (%) from different sources to respective demand in Eastern region.

Year	Domestic sector		Agricultural sector		Industrial sector
	GW	DW	GW	TWW	GW
2015	13.0	87.0	57.3	42.7	100.0
2020	13.0	87.0	53.1	46.9	100.0
2025	11.4	88.6	48.4	51.6	100.0
2030	8.2	91.8	43.3	56.7	100.0
2035	4.9	95.1	37.8	62.2	100.0
2040	1.9	98.1	31.6	68.4	100.0
2045	0.3	99.7	25.5	74.5	100.0
2050	0.0	100.0	19.3	80.7	100.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.6.2 Water Quality Satisfaction

Table 5.14 presents the achieved TDS of water supplied to various sectors for the period of 2015 through 2050. The priorities, R_2, R_4 and R_6 were achieved successfully, indicating the achievement of target TDS in each sector.. From 2025-2050, decrease of GW in water blending stations let the blended water to have TDS in the range of 50 - 442.1 ppm. The TDS of water supplied from a single source needs to be controlled at the supply source through treatment.

Table 5.14: Water quality achievement in terms of TDS (ppm) for various demand sectors in Eastern region.

Year	Domestic sector	Agricultural sector		Industrial sector
	Blended water (GW + DW)	GW	TWW	GW
2015	500.0	3500.0	2000.0	300.0
2020	500.0	3500.0	2000.0	300.0
2025	442.1	3500.0	2000.0	300.0
2030	334.5	3500.0	2000.0	300.0
2035	217.4	3500.0	2000.0	300.0
2040	115.2	3500.0	2000.0	300.0
2045	61.9	3500.0	2000.0	300.0
2050	50.0	3500.0	2000.0	300.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.6.3 Source Wise Predicted Water Demands

The predicted quantities of water to be allocated from GW, DW and TWW show increasing trend with time. In 2015, the demand for GW, DW and TWW is 747.1, 341.3 and 313.6 MCM respectively, which will be 1923, 758.4 and 592.7 MCM in 2050 respectively, indicating an average increase of approximately 4.5%, 3.5% and 2.5% per year respectively. It is to be noted that GW is likely to satisfy more than half (53.3-58.7%) of total water demands, while the remaining is satisfied by DW supply (23.2-24.3%) and TWW reuse (18.1-22.4%).

The present withdrawal of GW is 1030.2 MCM/year [21], which may successfully satisfy the predicted quantity for up to 2030. In 2035, 2040, 2045 and 2050, there is a need of additional 72.9, 256.3, 521.9 and 892.8 MCM of GW respectively (Figure 5.14a). The current supply of DW is 316 MCM/year [21], which is not adequate to satisfy the predicted quantity in all years (Figure 5.14b). This means additional supply of DW is needed. In 2015, there is a need to supply 341.3 MCM of DW, which is 25.3 MCM more than the current DW supply. Further, DW supply needs to be increased to 758.4 MCM by 2050, which is 442.4 MCM more than the current supply. In context to TWW, the current capacity of sewage plants showed positive deviations in all years (Figure 5.14c); meaning that the predicted quantity of TWW is likely to be satisfied (the priority R_7 was successfully achieved). However, the historical data revealed that around 472.1 MCM/year of generated wastewater is being treated while only 73.5 MCM/year of TWW is recycled for reuse [21]. The TWW needs to be fully recycled for agricultural uses.

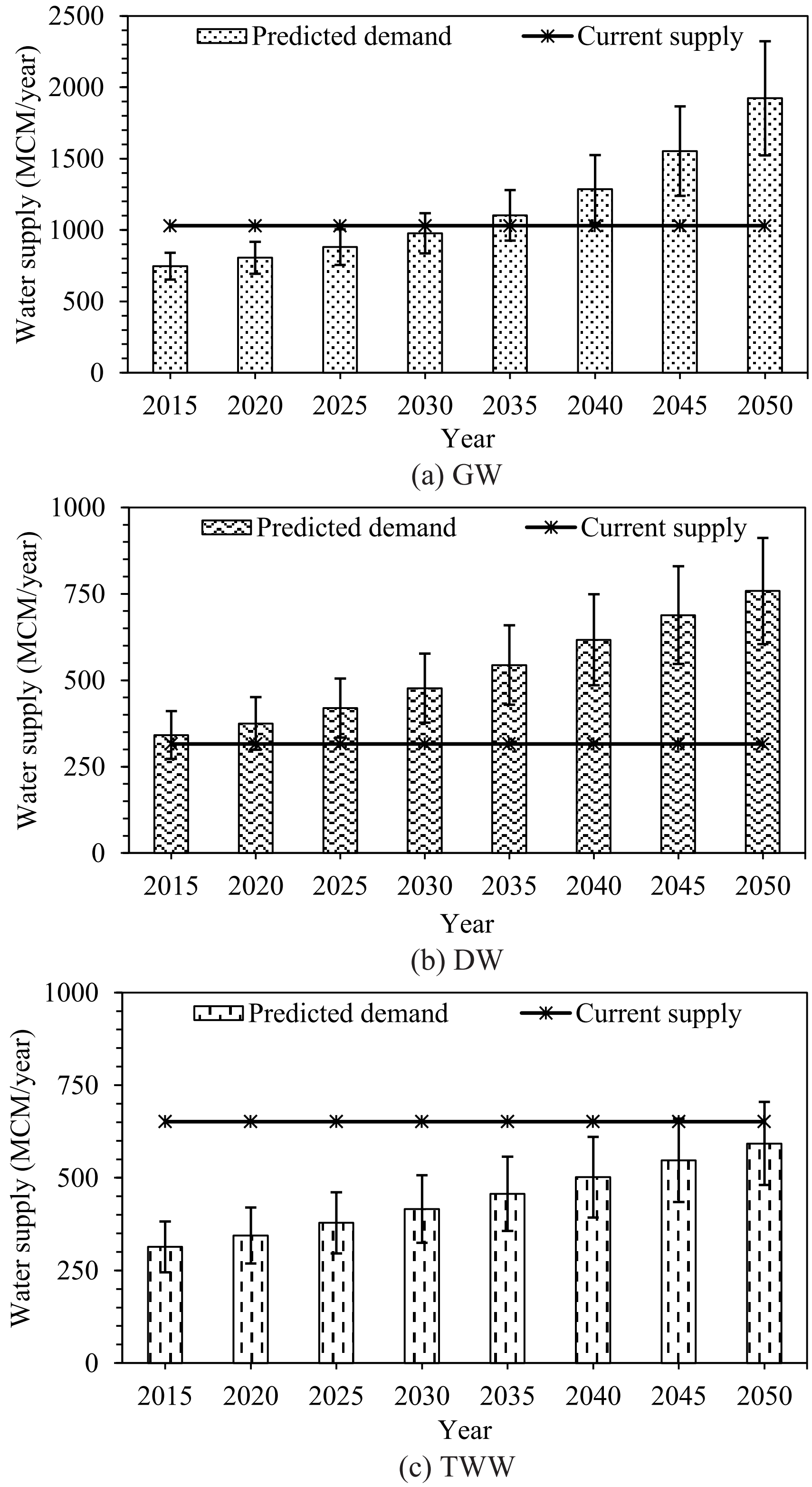


Figure 5.14: Predicted water demands from current supply sources in Eastern region.

Error bars represent the standard deviations.

Table 5.15 shows the probabilities of satisfying the predicted quantity of water from different sources. The current rate of GW supply is likely to deliver the predicted quantities in 2015 and 2020, while from 2025 to 2045, the probability of non-satisfying the predicted quantities may increase from 12% to 97%. In 2050, the current rate of GW extraction cannot satisfy the predicted quantity. The probability for satisfying the predicted DW in full may decrease from 29% in 2015 to 1.0% in 2040. In 2045 and 2050, the current supply of DW cannot satisfy the predicted quantity. The existing wastewater plants are likely to deliver the predicted quantities of TWW from 2015 to 2030, while from 2035 to 2050, the probability of non-satisfying the predicted TWW may increase from 3% to 37%.

Table 5.15: Probabilities of satisfying the predicted water from current supply sources in Eastern region (%).

Source / Year	GW	DW	TWW
2015	100.0	29.0	100.0
2020	100.0	21.0	100.0
2025	88.0	13.0	100.0
2030	62.0	5.0	100.0
2035	36.0	3.0	97.0
2040	14.0	1.0	90.0
2045	3.0	0.0	79.0
2050	0.0	0.0	63.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.6.4 Cost of Water Supply

Figure 5.15 shows the costs of using water from different sources. The cost of using predicted quantities of GW, DW and TWW in 2015 are approximately 1372.9, 2354.6 and 1681.9 million SR respectively. In 2050, these costs have been estimated to be 3533.6, 5232.8 and 3178.1 million SR, respectively. The cost of DW supply is likely to exceed the cost for GW and TWW in all years. The overall cost for supplying water from various sources has been estimated to be 5.4 billion US$ in 2015, which may be increased to 11.9 billion SR in 2050.

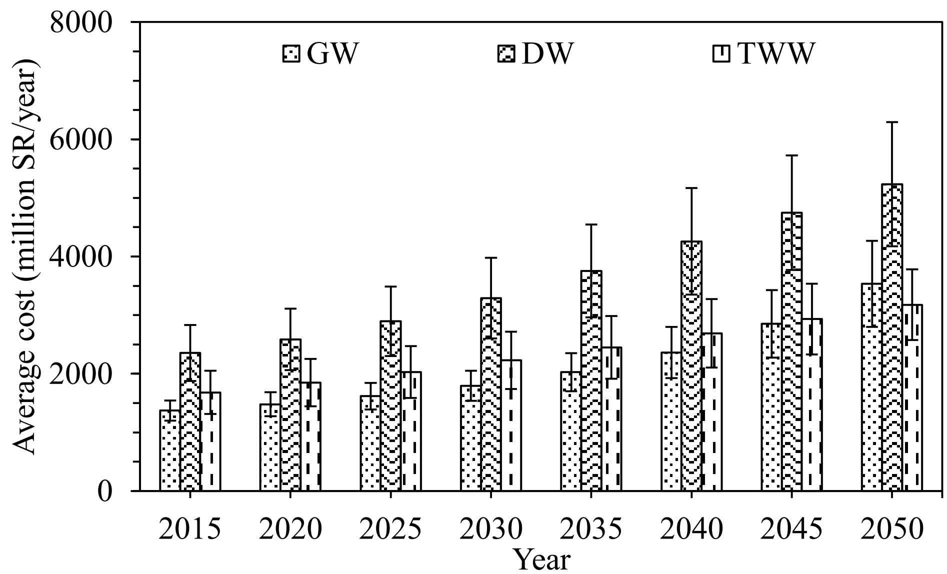


Figure 5.15: Average cost of supplying the predicted quantities of water from different sources in Eastern region: Mean (bars) and standard deviation (error bars).

5.7 Aseer Region

5.7.1 Sector Wise Water Demands Satisfaction

Figure 5.16 shows the water demands in domestic, agricultural and industrial sectors and the predicted contributions from different sources. The domestic water demand is satisfied by GW, SW and DW. In 2015, the domestic water demand is 138.6 MCM, which is anticipated to be 277.4 MCM in 2050 (Figure 5.16a). From 2015 through 2050, GW and DW contributions are forecasted to increase from 12.4 and 82.4 MCM to 30.4 and 203.1 MCM respectively. SW supply to domestic sector may increase from 43.8 MCM in 2015 to 45.5 MCM in 2030. In 2035 and 2040, the SW is fully supplied for domestic purposes. In 2045 and 2050, SW supply to domestic sector is predicted to be 45.6 and 43.9 MCM respectively (Figure 5.16a). The agricultural demand is 330 MCM/year, which is satisfied by GW, SW and TWW. From 2015-2050, GW supply to agricultural sector may gradually decrease from 217.3 MCM to 106.6 MCM, indicating an annual decrease of approximately 1.5% per year (Figure 5.16b). SW withdrawal for agriculture may reduce from 1.9 MCM in 2015 to 0.2 MCM in 2030. In 2035 and 2040, there will be no SW for agriculture. Reuse of TWW in agricultural sector is estimated to increase from 110.8 MCM in 2015 to 221.6 MCM by 2050. The water demand in industrial sector is fully satisfied by GW, which will be increased from 22.3 MCM in 2015 to 149.1 MCM by 2050 (Figure 5.16c).

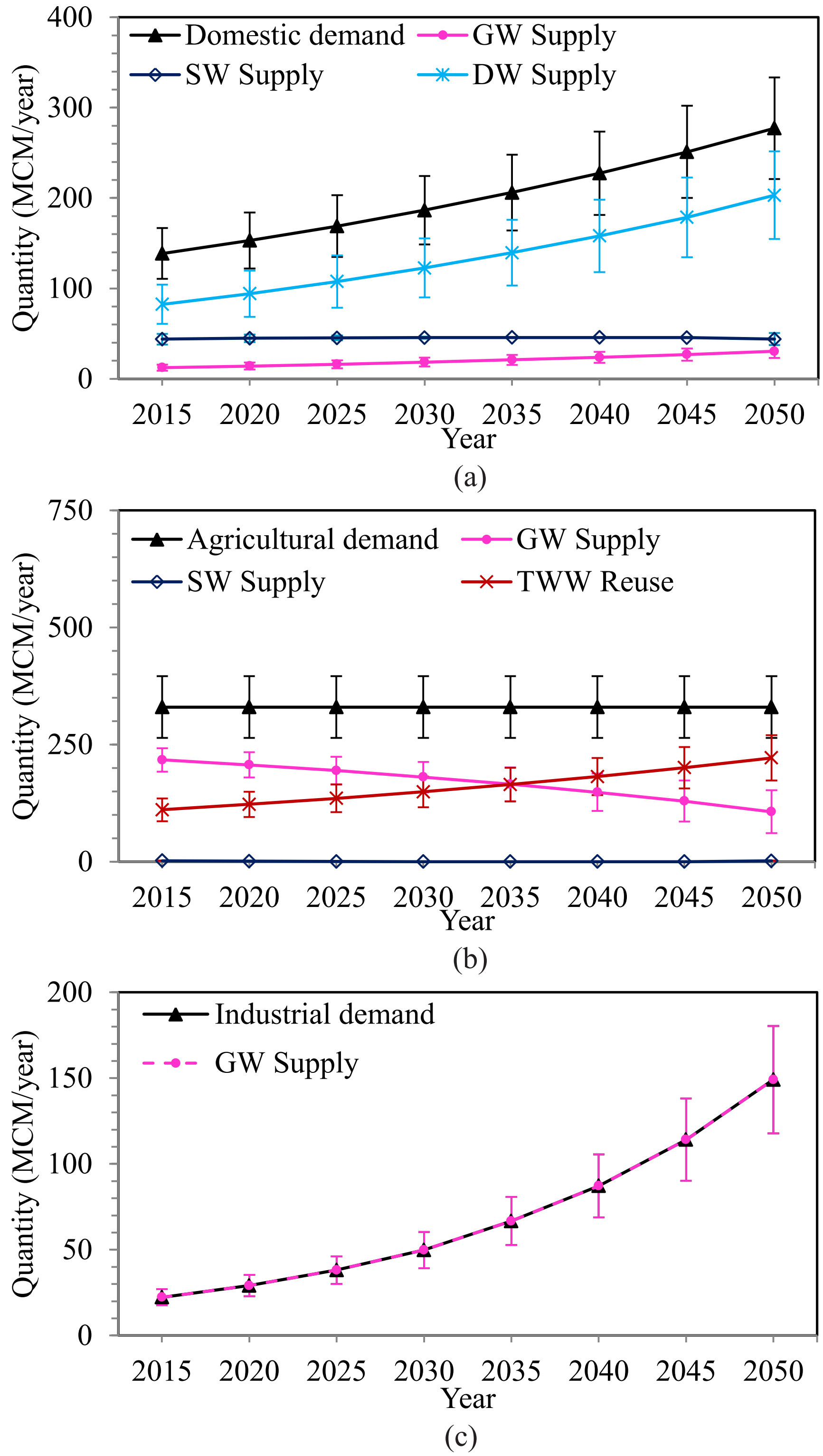


Figure 5.16: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Aseer region: Mean (solid lines) and standard deviations (error bars).

The water contributions from multiple sources to multiple sectors are given in Table 5.16. Approximately 8.8%, 32.3% and 58.9% of domestic water demand in 2015 is likely to be satisfied by GW, SW and DW respectively. In 2050, these proportions are observed to be 10.9%, 16.4% and 72.7% respectively. It is to be noted that the contribution of GW and DW in domestic sector from 2015 through 2050 is expected to have an increase of approximately 2.1% and 13.8% respectively, while SW contribution may have a reduction of approximately 15.9%. From 2015 to 2050, GW contribution in agricultural sector is expected to decrease from 65.9% to 32.3% (approximately 1.5% decrease annually). During this period, contribution of TWW reuse to agriculture may increase from 33.5% to 67.1% (approximately 2.9% increase per year). Water demands in industrial sector from 2015 through 2050 will be fully satisfied by GW supply.

Table 5.16: Water supply contribution (%) from different sources to respective demand in Aseer region.

Year	Domestic sector			Agricultural sector			Industrial sector
	GW	SW	DW	GW	SW	TWW	GW
2015	8.8	32.3	58.9	65.9	0.6	33.5	100.0
2020	9.1	30.2	60.7	62.6	0.3	37.1	100.0
2025	9.4	27.8	62.8	58.9	0.2	40.9	100.0
2030	9.7	25.5	64.8	54.8	0.05	45.2	100.0
2035	10.0	23.2	66.8	50.1	0.0	49.9	100.0
2040	10.3	21.0	68.7	44.9	0.0	55.1	100.0
2045	10.6	19.0	70.4	39.2	0.0	60.8	100.0
2050	10.9	16.4	72.7	32.3	0.6	67.1	100.0

GW: Groundwater; DW: Desalinated water; SW: Surface water; TWW: Treated wastewater.

5.7.2 Water Quality Satisfaction

The achieved water qualities from 2015 through 2050 are shown in Table 5.17. The target TDS for each sector was satisfied, indicating the achievement of priorities, R_2, R_4 and R_6. In domestic sector, the TDS for blended water in 2015 and 2020 is 499.9 ppm. From 2025 through 2045, the TDS level of blended water is equal to the maximum allowable level of 500 ppm. In 2050, this will be 499.7 ppm.

Table 5.17: Water quality achievement in terms of TDS (ppm) for various demand sectors in Aseer region.

Year	Domestic sector		Agricultural sector			Industrial sector
	Blended water (GW + DW)	SW	GW	SW	TWW	GW
2015	499.9	225	3500	225	2000	300
2020	499.9	225	3500	225	2000	300
2025	500.0	225	3500	225	2000	300
2030	500.0	225	3500	225	2000	300
2035	500.0	225	3500	–	2000	300
2040	500.0	225	3500	–	2000	300
2045	500.0	225	3500	–	2000	300
2050	499.7	225	3500	225	2000	300

GW: Groundwater; DW: Desalinated water; SW: Surface water; TWW: Treated wastewater.

5.7.3 Source Wise Predicted Water Demands

Figure 5.17 presents the predicted demands of water to be supplied from various sources for the period of 2015-2050. Extraction of GW is expected to be reduced from 252 MCM in 2015 to 248.7 MCM in 2025. From 2025 to 2030, insignificant increase (around 0.1 MCM) may take place. In 2050, this increase is projected to be approximately 37.4 MCM, meaning that GW extraction will be 286.1 MCM (Figure

5.17a). The available SW (45.7 MCM/year) was fully allocated for satisfying water demands in domestic and agricultural sectors (Figure 5.17b). In case of DW, about 82.4 MCM is needed in 2015, which is estimated to be 203.1 MCM in 2050 (Figure 5.17c). In 2015, domestic sector is expected to generate about 110.8 MCM of wastewater, which is likely to increase to 221.6 MCM in 2050 (Figure 5.17d).

With reference to water availability, the current supply of GW, SW, DW and TWW was assumed to be 372.3, 45.7, 54 and 133.8 MCM/year respectively [21]. There is no need to extract additional quantities above the present supply of GW throughout the period of 2015 to 2050, meaning that the priority to minimize GW extraction (R_9) was achieved (Figure 5.17a). The priority to maximize SW use (R_8) was achieved successfully, showing the full allocation of the stored SW in all years (Figure 5.17b). The results demonstrate that the achievement of priority R_{10} to minimize the overproduction of DW was not achieved in any year, which means the current supply of DW is not adequate to meet the predicted quantities (Figure 5.17c). In 2015, supply of DW is estimated to be 28.4 MCM more than the current level, which is forecasted to be 149.1 MCM in 2050. In case of TWW, the existing capacity of wastewater plants is adequate to treat the domestic wastewater in full only in 2015 and 2020. Thereafter, the current capacity of sewage plants is not adequate to fully treat the generated wastewater (Figure 5.17d). Presently, only 34.8 MCM/year of wastewater is being treated in Asser region, while about half (roughly 17.5 MCM/year) of TWW is recycled for reuse [21].

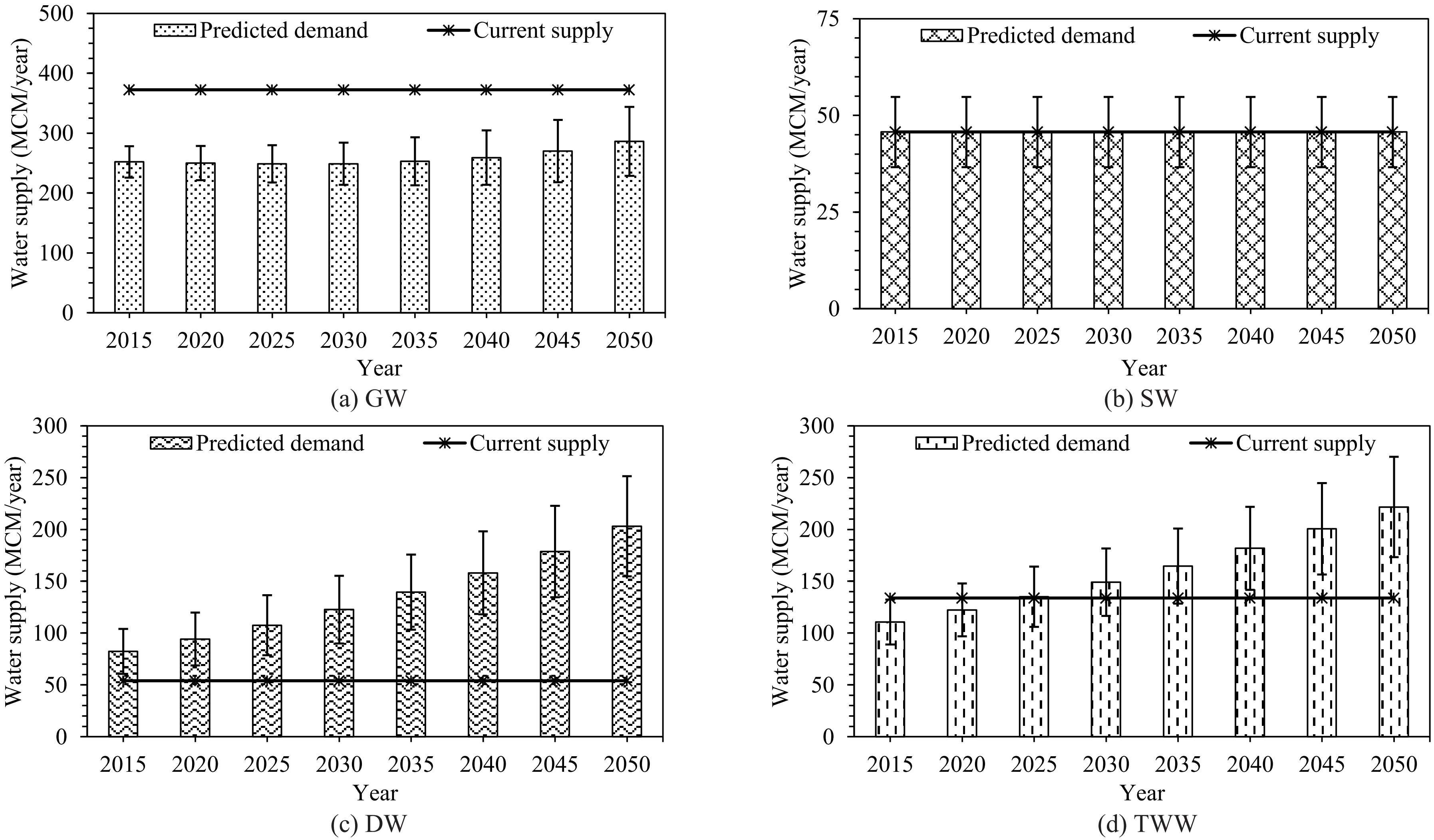


Figure 5.17: Predicted water demands from current supply sources in Aseer region. Error bars represent the standard deviations.

According to Table 5.18, the current rate of GW extraction is likely to satisfy the predicted quantities till 2040; while in 2045 and 2050, the probabilities of satisfying the predicted GW are expected to be 99% and 94% respectively. In 2015, the chance for satisfying the predicted quantity of DW in full is 7%, which may decrease to 1% in 2035. Beyond 2035, the current supply of DW cannot satisfy the predicted quantity in any year. The probability of satisfying the predicted quantity of TWW by the current sewage capacity is expected to decrease from 83% in 2015 to 3% by 2050 (approximately 2.8% decrease per year).

Table 5.18: Probabilities of satisfying the predicted water from current supply sources in Aseer region (%).

Year \ Source	GW	SW	DW	TWW
2015	100.0	100.0	7.0	83.0
2020	100.0	100.0	4.0	63.0
2025	100.0	100.0	2.0	49.0
2030	100.0	100.0	2.0	33.0
2035	100.0	100.0	1.0	20.0
2040	100.0	100.0	0.0	12.0
2045	99.0	100.0	0.0	6.0
2050	94.0	100.0	0.0	3.0

GW: Groundwater; DW: Desalinated water; SW: Surface water; TWW: Treated wastewater.

5.7.4 Cost of Water Supply

The costs of using water from different sources have been summarized in Figure 5.18. The cost for supplying the predicted quantity of GW may decrease from 463.1 million SR in 2015 to 457.1 million SR in 2025. However, there will be an increasing trend for the cost of using GW starting beyond 2025, which will reach to approximately 525.8 million

SR in 2050. The cost for supplying SW is likely to be 84 million SR annually. Supplying the predicted quantity of DW in 2015 is expected to cost 568.9 million SR, which is forecasted to be to 1401 million SR by 2050 (approximately 4.2 % increase per year). In 2015, the cost for reusing TWW was estimated to be 594 million SR, which will increase to 1188.4 million SR in 2050. It is to be noted that the cost for reusing TWW in 2050 is twice that in 2015. The total cost of using water from different sources has been estimated to be 1.7 billion SR in 2015, which may increase to 3.2 billion SR in 2050.

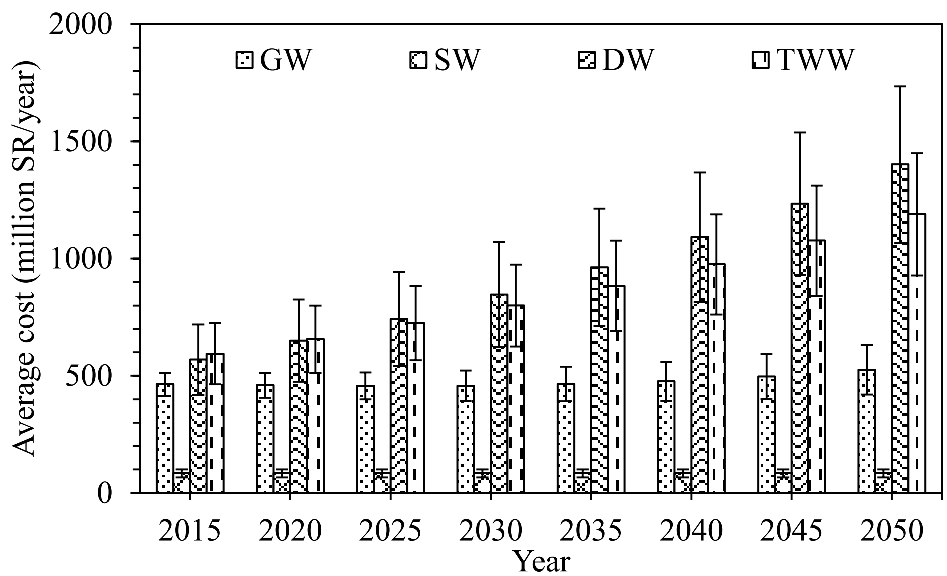


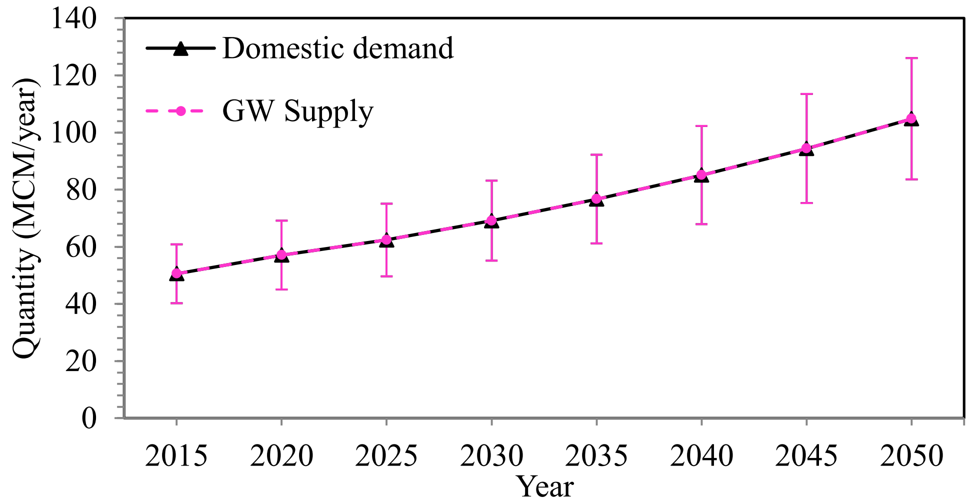
Figure 5.18: Average cost of supplying the predicted quantities of water from different sources in Aseer region: Mean (bars) and standard deviation (error bars).

5.8 Hail Region

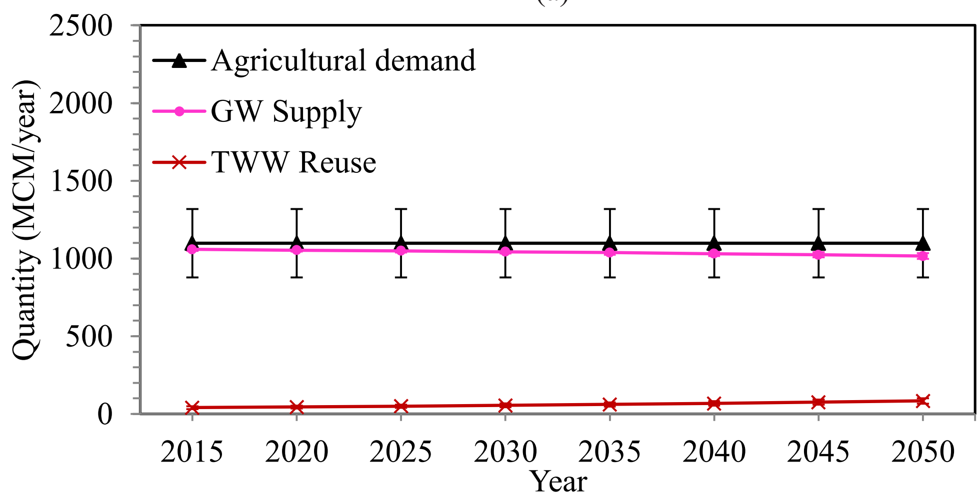
5.8.1 Sector Wise Water Demands Satisfaction

Figure 5.19 shows the satisfaction of sector wise water demands. Figure 5.19a indicates that the domestic water demand is likely to increase from 50.6 MCM in 2015 to 104.8 MCM in 2050, which is fully satisfied by GW. The agricultural water demand is

1099 MCM/year, which is satisfied by GW and TWW. GW extraction for agriculture will be reduced from 1058.5 MCM in 2015 to 1015.3 MCM in 2050. TWW reuse in agricultural sector needs to be maximized from 40.5 MCM in 2015 to 83.7 MCM in 2050 (Figure 5.19b). The industrial water demand is predicted to increase from 9.8 MCM in 2015 to 72.7 MCM by 2050, which is satisfied by GW (Figure 5.19c).



(a)



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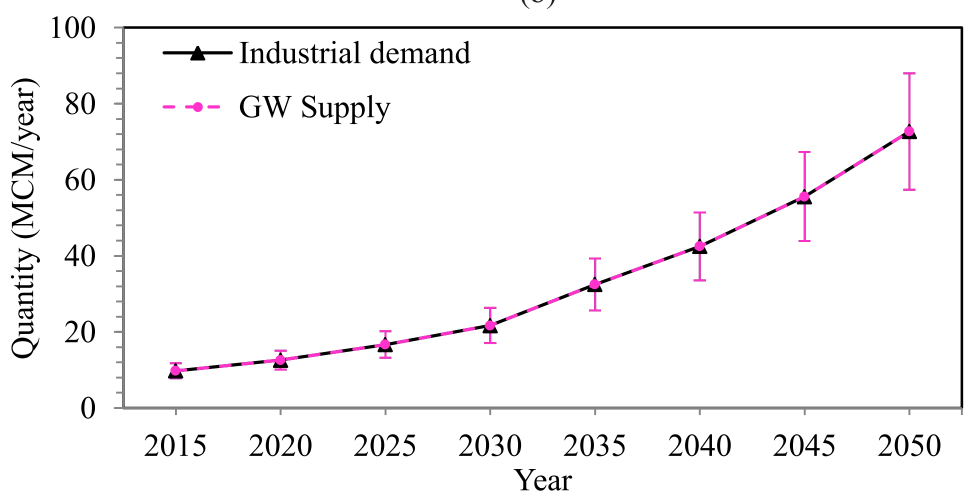


(c)

Figure 5.19: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Hail region: Mean (solid line) and standard deviations (error bars).

Table 5.19 details the percentages of water contribution from various sources to the consumption sectors. The water demand in the domestic sector from 2015 through 2050 is fully satisfied by GW. The contribution of GW in agriculture sector is estimated to reduce from 96.3 in 2015 to 92.4% in 2050 (3.9% reduction). TWW needs to satisfy 3.7% of agricultural water demand in 2015, and it is likely to be increased to 7.6% by 2050. The water demand in the industrial sector from 2015 through 2050 is fully satisfied by GW.

Table 5.19: Water supply contribution (%) from different sources to respective demand in Hail region.

Year	Domestic sector	Agricultural sector		Industrial sector
	GW	GW	TWW	GW
2015	100.0	96.3	3.7	100.0
2020	100.0	95.9	4.1	100.0
2025	100.0	95.5	4.5	100.0
2030	100.0	95.0	5.0	100.0
2035	100.0	94.4	5.6	100.0
2040	100.0	93.8	6.2	100.0
2045	100.0	93.1	6.9	100.0
2050	100.0	92.4	7.6	100.0

GW: Groundwater; TWW: Treated wastewater.

5.8.2 Water Quality Satisfaction

The TDS levels for various demand sectors from 2015 through 2050 are summarized in Table 5.20. The TDS of water to be supplied from a single source for a specific purpose needs to be controlled at the supply source through treatment.

Table 5.20: Water quality achievement in terms of TDS (ppm) for various demand sectors in Hail region.

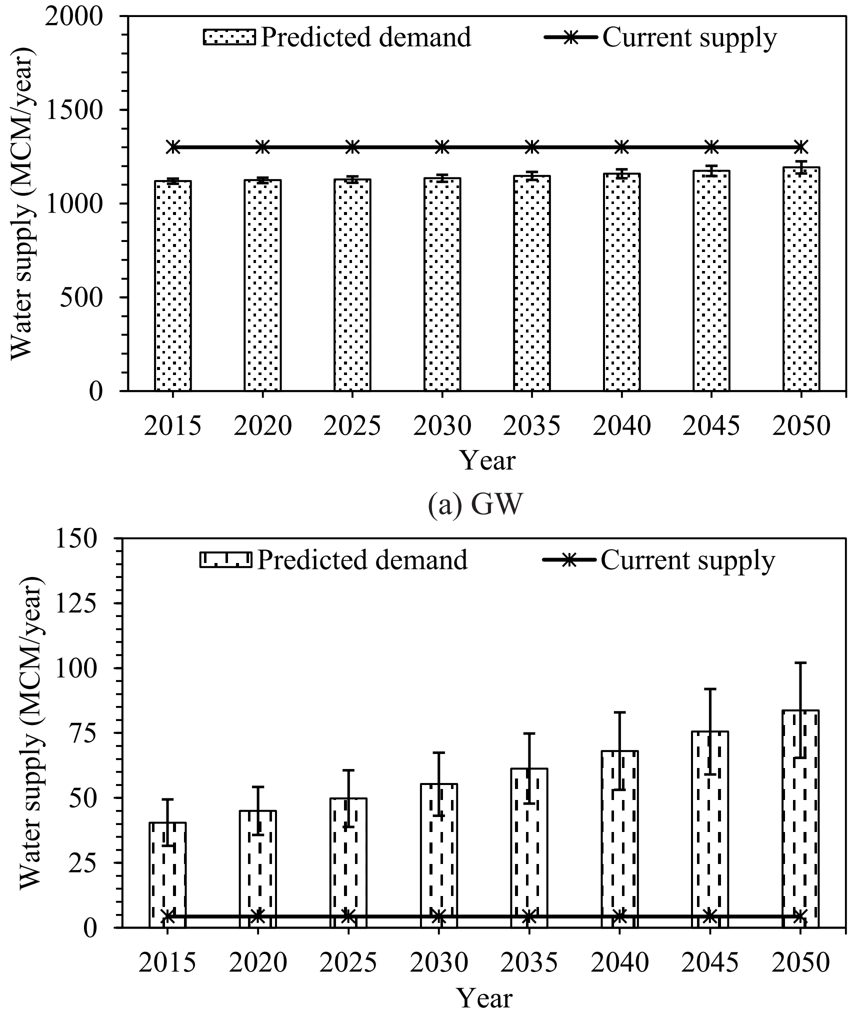
Year	Domestic sector	Agricultural sector		Industrial sector
	GW	GW	TWW	GW
2015	300	3500	2000	300
2020	300	3500	2000	300
2025	300	3500	2000	300
2030	300	3500	2000	300
2035	300	3500	2000	300
2040	300	3500	2000	300
2045	300	3500	2000	300
2050	300	3500	2000	300

GW: Groundwater; TWW: Treated wastewater.

5.8.3 Source Wise Predicted Water Demands

Figure 5.20 shows the predicted quantities of water to be supplied from GW and TWW. In 2015, supplies of GW and TWW are 1119 and 40.5 MCM respectively, which is projected to increase to 1192.7 and 83.7 MCM respectively by 2050. Supply of GW and TWW needs to be increased to 1.1 and 2.1 folds to the water in 2015 respectively (Figure 5.20a, b).

GW resource showed positive deviations, meaning that the objective to maximize GW conservation was achieved. The maximum extraction of GW is 1192.7 MCM in 2050, which can be satisfied by the current rate of GW withdrawal. Assuming the constant supply of GW of 1300.5 MCM per year [21], this source satisfies the demands from 2015 through 2050 (Figure 5.20a). The current capacity of treatment plants is approximately 4.4 MCM/year [21], while generation of domestic wastewater in 2015 is approximately 40.5 MCM and it is expected to be 83.7 MCM in 2050 (Figure 5.20b). On the other side, only 6.2 MCM/year of generated wastewater is being treated [21]. Reuse of TWW in agricultural sector needs to be maximized. Consequently, building infrastructures to collect and treat the domestic wastewater is needed in order to maximize TWW for agricultural reuse.



(b) TWW

Figure 5.20: Predicted water demands from current supply sources in Hail region. Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of GW and TWW are shown in Table 5.21. The current rate of GW withdrawal is likely to deliver the predicted quantities from 2015 through 2050. During this period, the current capacity of wastewater plants cannot fully satisfy any of the 100 random scenarios assessed in this study.

Table 5.21: Probabilities of satisfying the predicted water from current supply sources in Hail region (%).

Source / Year	GW	TWW
2015	100.0	0.0
2020	100.0	0.0
2025	100.0	0.0
2030	100.0	0.0
2035	100.0	0.0
2040	100.0	0.0
2045	100.0	0.0
2050	100.0	0.0

GW: Groundwater; TWW: Treated wastewater.

5.8.4 Cost of Water Supply

The average costs of using water from different sources are presented in Figure 5.21. The costs of using GW and TWW in 2015 are approximately 2056.1 and 217.1 million SR respectively. In 2050, these costs have been estimated to be 2191.5 and 448.9 million SR respectively. The total cost of using water from different sources has been estimated to be 2.3 billion SR in 2015, which is predicted to be 2.6 billion SR in 2050.

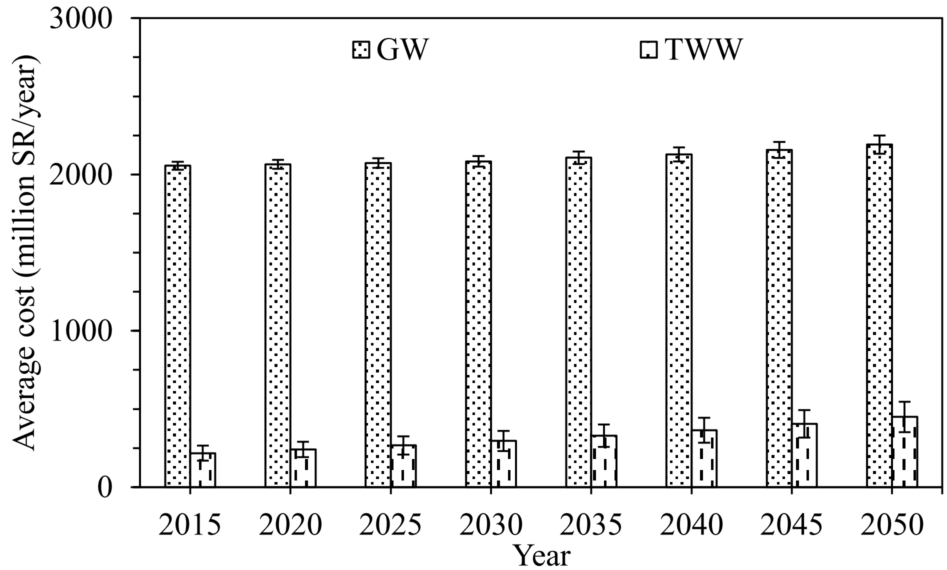


Figure 5.21: Average cost of supplying the predicted quantities of water from different sources in Hail region: Mean (bars) and standard deviation (error bars).

5.9 Tabouk Region

5.9.1 Sector Wise Water Demands Satisfaction

Figure 5.22 shows the satisfaction of sector wise water demands. Figure 5.22a indicates that the domestic water demand in 2015 is 76.3 MCM, which is satisfied by 10 and 66.3 MCM of GW and DW respectively. In 2050, distribution of GW and DW is estimated to be 22 and 147 MCM respectively. For agriculture, GW extraction will be reduced from 504.1 MCM in 2015 to 429.9 MCM in 2050, indicating an average reduction of approximately 0.4% per year (Figure 5.22b). TWW reuse in agricultural sector needs to be maximized from 60.9 MCM in 2015 to 135.1 MCM in 2050 (Figure 5.22b). The industrial water demand is predicted to increase from 11.1 MCM in 2015 to 77.9 MCM by 2050 (Figure 5.22c).

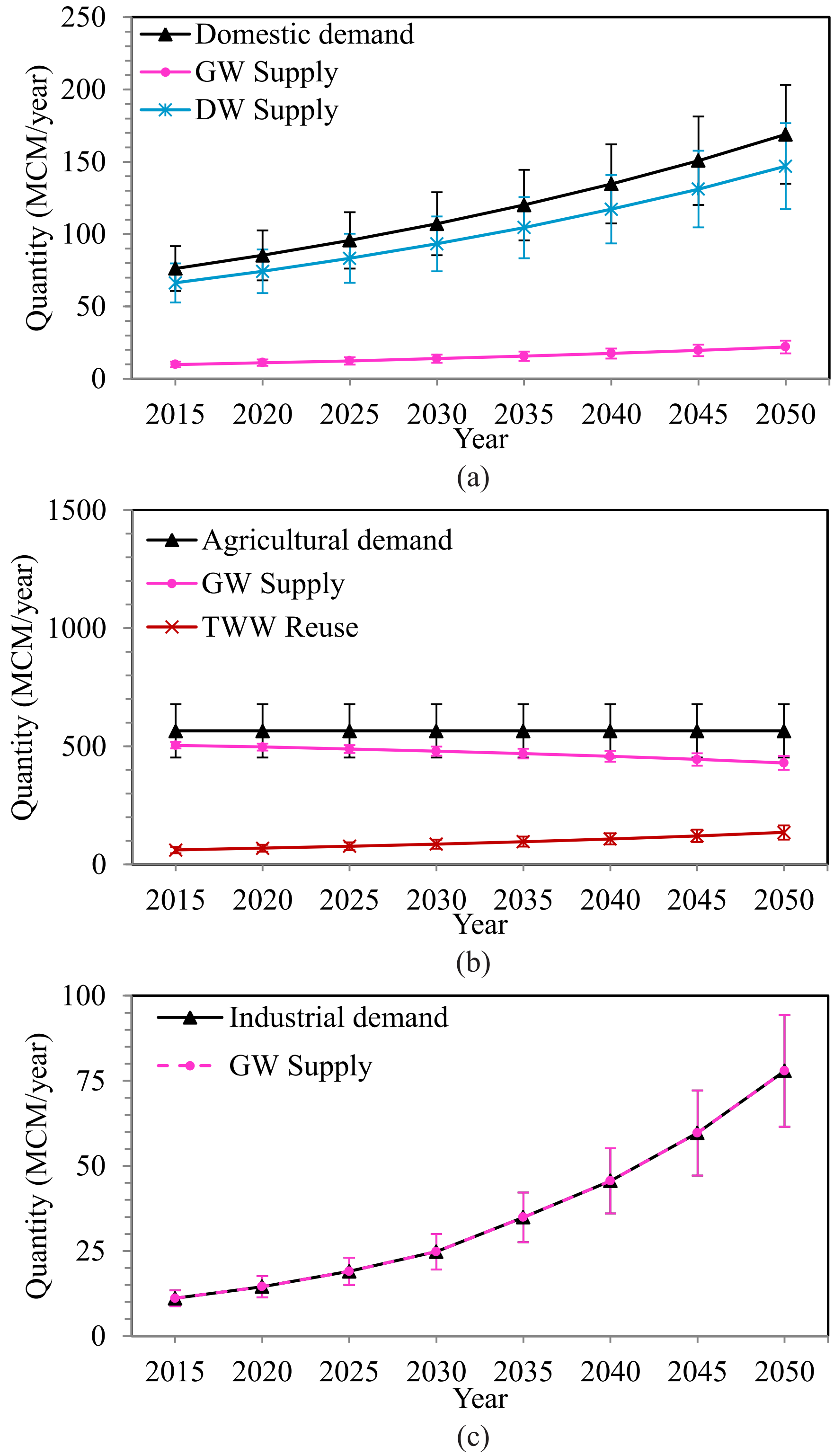


Figure 5.22: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Tabouk region: Mean (solid line) and standard deviations (error bars).

Table 5.22 details the percentages of water contribution from various sources to the consumption sectors. GW contribution to domestic sector from 2015 through 2050 was approximately 13%. Throughout these years, DW satisfies 87% of domestic water demands. The contribution of GW to agriculture sector is estimated to reduce from 89.2% in 2015 to 76.1 % in 2050 (13.1% reduction). TWW needs to satisfy 10.8% of agricultural water demand in 2015, and it is likely to be increased to 23.9% by 2050. The water demand in the industrial sector from 2015 through 2050 is fully satisfied by GW.

Table 5.22: Water supply contribution (%) from different sources to respective demand in Tabouk region.

Year	Domestic sector		Agricultural sector		Industrial sector
	GW	DW	GW	TWW	GW
2015	13.0	87.0	89.2	10.8	100.0
2020	13.0	87.0	87.9	12.1	100.0
2025	13.0	87.0	86.5	13.5	100.0
2030	13.0	87.0	84.8	15.2	100.0
2035	13.0	87.0	83.0	17.0	100.0
2040	13.0	87.0	81.0	19.0	100.0
2045	13.0	87.0	78.7	21.3	100.0
2050	13.0	87.0	76.1	23.9	100.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.9.2 Water Quality Satisfaction

The TDS levels for various sectors from 2015 through 2050 are shown in Table 5.23. The TDS of blended water for domestic sector is equal to the maximum allowable level in all years. The TDS of water to be supplied from a single source for a specific purpose needs to be controlled at the supply source through treatment.

Table 5.23: Water quality achievement in terms of TDS (ppm) for various demand sectors in Tabouk region.

Year	Domestic sector	Agricultural sector		Industrial sector
	Blended water (GW + DW)	GW	TWW	GW
2015	500.0	3500.0	2000.0	300.0
2020	500.0	3500.0	2000.0	300.0
2025	500.0	3500.0	2000.0	300.0
2030	500.0	3500.0	2000.0	300.0
2035	500.0	3500.0	2000.0	300.0
2040	500.0	3500.0	2000.0	300.0
2045	500.0	3500.0	2000.0	300.0
2050	500.0	3500.0	2000.0	300.0

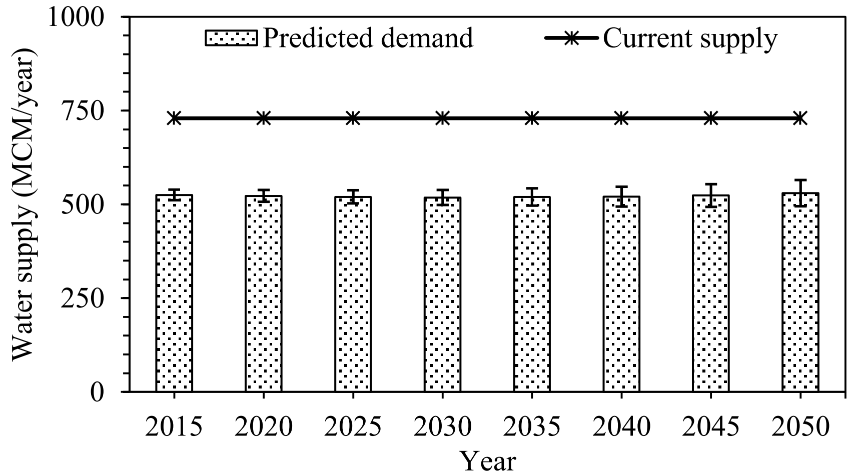
GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.9.3 Source Wise Predicted Water Demands

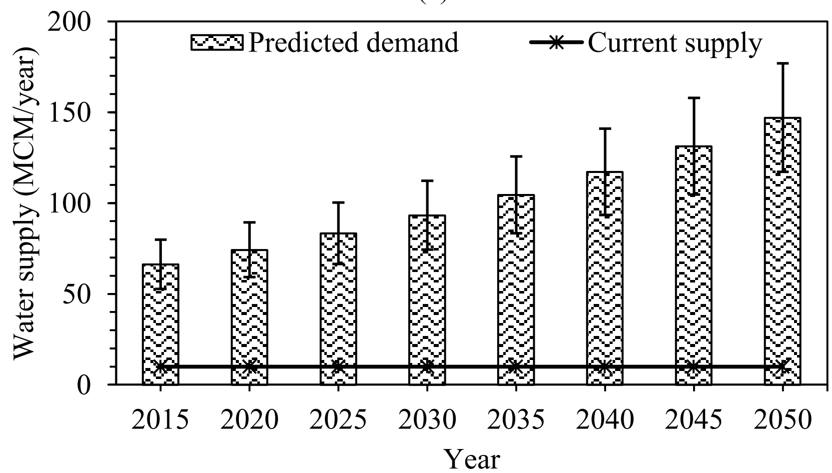
Figure 5.23 displays the predicted amounts of water to be supplied from GW, DW and TWW. In 2015, water supplies of GW, DW and TWW are 525.1, 66.3 and 60.9 MCM respectively, which are projected to increase to 529.8, 147 and 135.1 MCM respectively by 2050. Supply of DW and TWW needs to be increased to approximately 2.2 folds to the water in 2015 respectively (Figure 5.23b, c), while GW is likely to be increased by approximately 0.03% per year (Figure 5.23a).

The maximum extraction of GW is 529.8 MCM in 2050, which can be satisfied by the current rate of GW withdrawal. Assuming the constant supply of GW of 729.8 MCM per year [21], this source satisfies the demands from 2015 through 2050 (Figure 5.23a). However, additional DW is needed in all the years. Currently, supply of DW is approximately 10 MCM per year [21]. To satisfy domestic water demands from 2015 through 2050, there is a need of additional 56.3 MCM of DW in 2015 and 137 MCM of

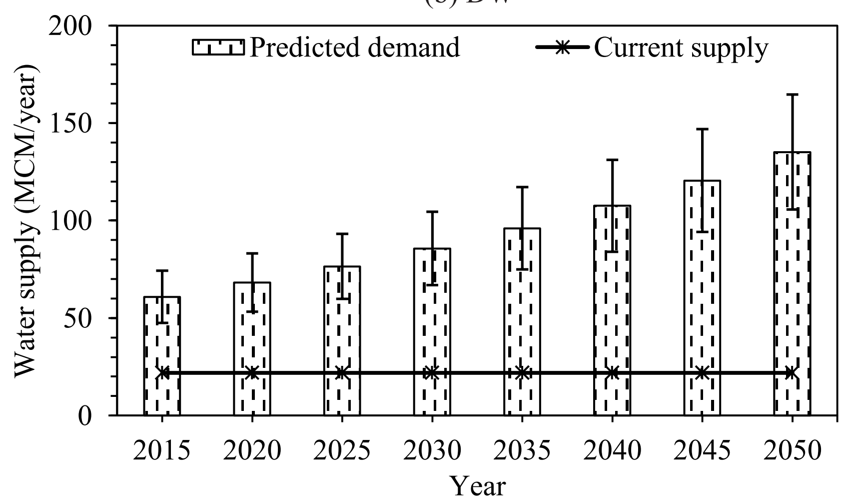
DW in 2050. The current capacity of wastewater plants is approximately 21.9 MCM per year [21], while generation of domestic wastewater in 2015 is approximately 60.9 MCM and it is expected to be 135.1 MCM in 2050 (Figure 5.23c). Reuse of TWW in agricultural sectors needs to be maximized.



(a) GW



(b) DW



(c) TWW

Figure 5.23: Predicted water demands from current supply sources in Tabouk region.

Error bars represent the standard deviations.

Table 5.24 indicates the probabilities of satisfying the predicted quantities of GW, DW and TWW. The current rate of GW extraction is likely to deliver predicted quantities in all years. The current supply of DW and TWW cannot satisfy predicted quantities in full in any year.

Table 5.24: Probabilities of satisfying the predicted water from current supply sources in Tabouk region (%).

Source / Year	GW	DW	TWW
2015	100.0	0.0	0.0
2020	100.0	0.0	0.0
2025	100.0	0.0	0.0
2030	100.0	0.0	0.0
2035	100.0	0.0	0.0
2040	100.0	0.0	0.0
2045	100.0	0.0	0.0
2050	100.0	0.0	0.0

GW: Groundwater; DW: Desalinated water; TWW: Treated wastewater.

5.9.4 Cost of Water Supply

The average costs of using water from different sources are presented in Figure 5.24. The costs of using GW, DW and TWW in 2015 are approximately 964.9, 457.9 and 326.6 million SR respectively. In 2050, these costs have been estimated to be 973.5, 1014.8 and 724.5 million SR respectively. Among three supply sources, GW has the dominance of higher cost from 2015 to 2045, while in 2050 the cost for using DW is likely to exceed the cost for using GW. The total cost of using water from different sources has been estimated to be 1.7 billion SR in 2015, which is predicted to be 2.7 billion SR in 2050.

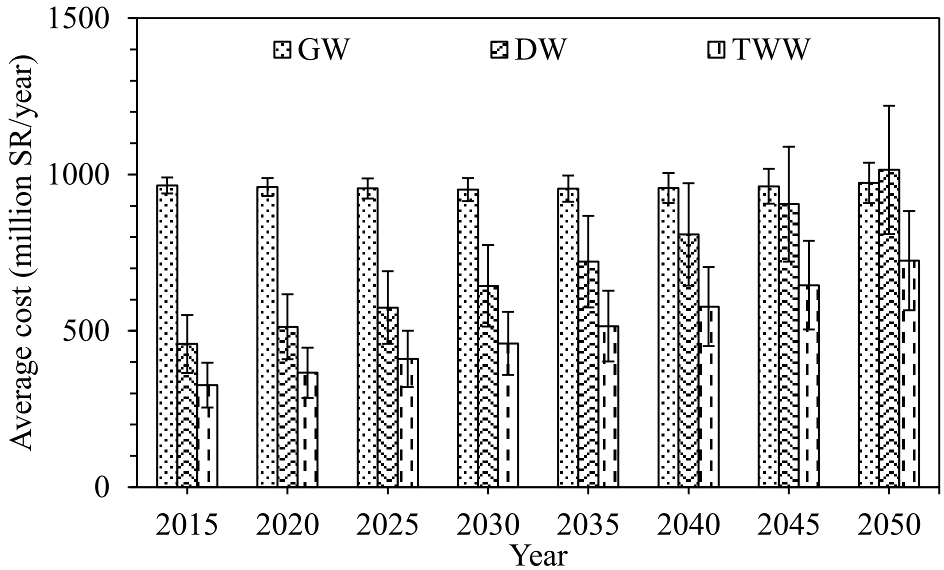
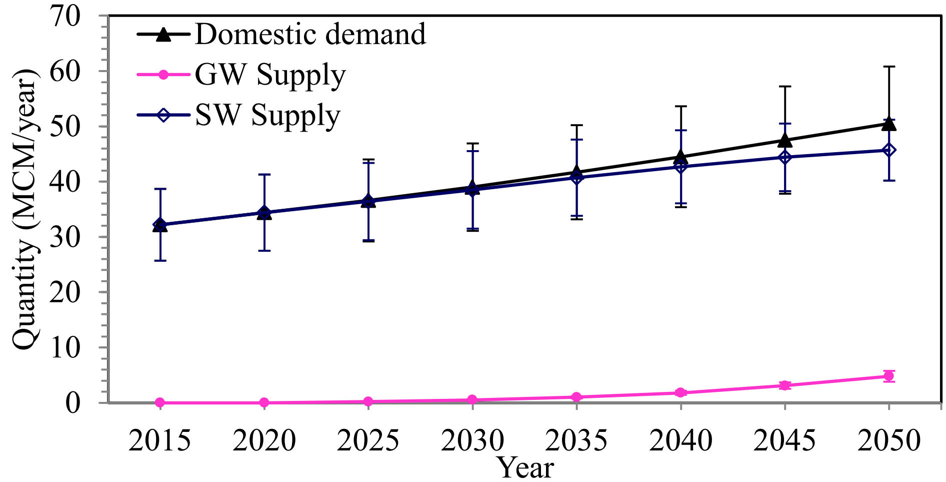


Figure 5.24: Average cost of supplying the predicted quantities of water from different sources in Tabouk region: Mean (bars) and standard deviation (error bars).

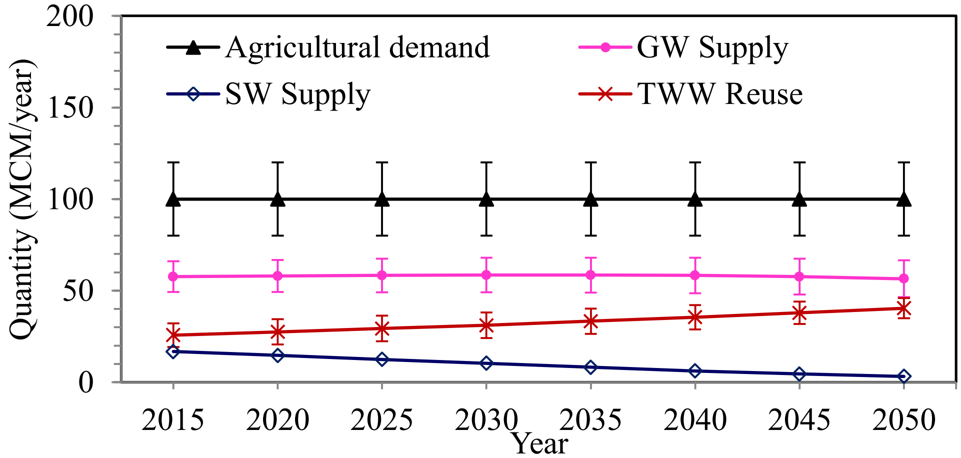
5.10 Al-Baha Region

5.10.1 Sector Wise Water Demands Satisfaction

Figure 5.25 shows the satisfaction of sector wise water demands. Figure 5.25a indicates that the domestic water demand in 2015 is 32.2 MCM, which is fully satisfied by SW. In 2050, this demand is predicted to be 50.5 MCM, which is satisfied by GW (4.8 MCM) and SW (45.7 MCM). In agriculture, GW supply will be reduced from 57.6 in 2015 to 56.5 MCM in 2050 (Figure 5.25b). The SW use in agriculture will be reduced from 16.7 MCM in 2015 to 3.2 MCM in 2050 (Figure 5.25b). TWW reuse in agricultural sector needs to be maximized from 25.7 MCM in 2015 to 40.4 MCM in 2050 (Figure 5.25b). The industrial water demand is predicted to increase from 7 MCM in 2015 to 50.3 MCM by 2050, which is satisfied by GW (Figure 25c).



(a)



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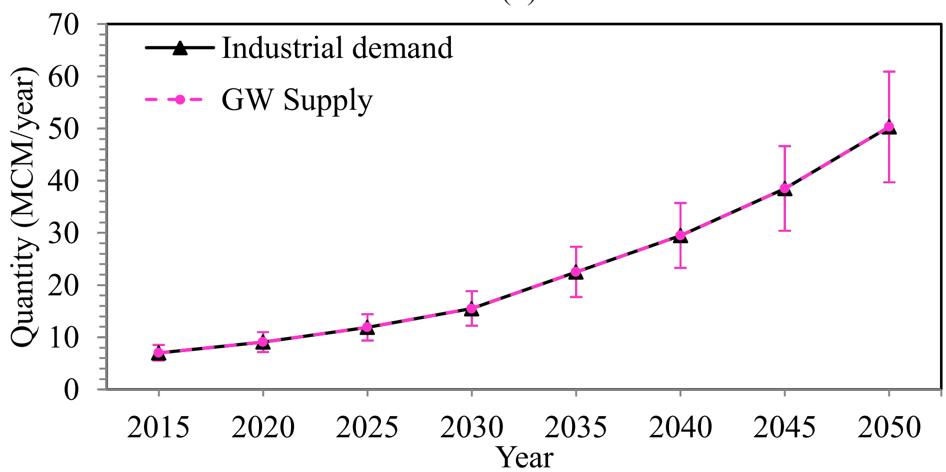


(c)

Figure 5.25: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Al-Baha region: Mean (solid line) and standard deviations (error bars).

Table 5.25 details the percentages of water contribution from various sources to the consumption sectors. In 2015, water demand in domestic sector is fully satisfied by SW. In 2050, GW and SW satisfy 7.7 and 92.3% of domestic water demands respectively. The contribution of GW and SW to agriculture sector is estimated to reduce from 57.6% and 16.7% respectively (2015) to 56.5% and 3.2% respectively (2050). TWW needs to satisfy 25.7% of agricultural water demand in 2015, and it is likely to be increased to 40.4% by 2050. The water demand in the industrial sector from 2015 through 2050 is fully satisfied by GW.

Table 5.25: Water supply contribution (%) from different sources to respective demand in Al-Baha region.

Year	Domestic sector		Agricultural sector			Industrial sector
	GW	SW	GW	SW	TWW	GW
2015	0.0	100.0	57.6	16.7	25.7	100.0
2020	0.0	100.0	58.0	14.5	27.5	100.0
2025	0.4	99.6	58.3	12.5	29.2	100.0
2030	0.9	99.1	58.5	10.4	31.1	100.0
2035	1.7	98.3	58.5	8.2	33.3	100.0
2040	3.0	97.0	58.3	6.2	35.5	100.0
2045	5.0	95.0	57.6	4.5	37.9	100.0
2050	7.7	92.3	56.5	3.2	40.4	100.0

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

5.10.2 Water Quality Satisfaction

The TDS levels for various sectors from 2015 through 2050 are shown in Table 5.26. The TDS of water to be supplied from a single source for a specific purpose needs to be controlled at the supply source through treatment.

Table 5.26: Water quality achievement in terms of TDS (ppm) for various demand sectors in Al-Baha region.

Year	Domestic sector		Agricultural sector			Industrial sector
	GW	SW	GW	SW	TWW	GW
2015	–	225	3500	225	2000	300
2020	–	225	3500	225	2000	300
2025	300	225	3500	225	2000	300
2030	300	225	3500	225	2000	300
2035	300	225	3500	225	2000	300
2040	300	225	3500	225	2000	300
2045	300	225	3500	225	2000	300
2050	300	225	3500	225	2000	300

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

5.10.3 Source Wise Predicted Water Demands

Figure 5.26 displays the predicted amounts of water to be supplied from GW, SW and TWW. In 2015, GW, SW and TWW supplies are 64.6, 48.9 and 25.7 MCM respectively, which are projected to be 111.5, 48.9 and 40.4 MCM respectively in 2050. Supply of GW and TWW needs to be increased to approximately 1.7 and 1.6 folds to the water in 2015 respectively (Figure 5.26a, c).

Assuming the constant supply of GW of 100.2 MCM per year [21], this source satisfies the demands till 2045 (Figure 5.26a). In 2050, the extraction of GW is 111.5 MCM, which is 11.3 MCM more than the current rate of GW withdrawal. The current SW (48.9 MCM/year) was fully allocated for satisfying water demands in domestic and agricultural sectors (Figure 5.26b). There are no wastewater plants in the region [21], while generation of domestic wastewater in 2015 is approximately 25.7 MCM and it is expected to be 40.4 MCM in 2050 (Figure 5.26c). Reuse of TWW in agricultural sectors needs to be maximized. Consequently, building infrastructures to collect and treat the domestic wastewater is needed to maximize TWW for agricultural reuse.

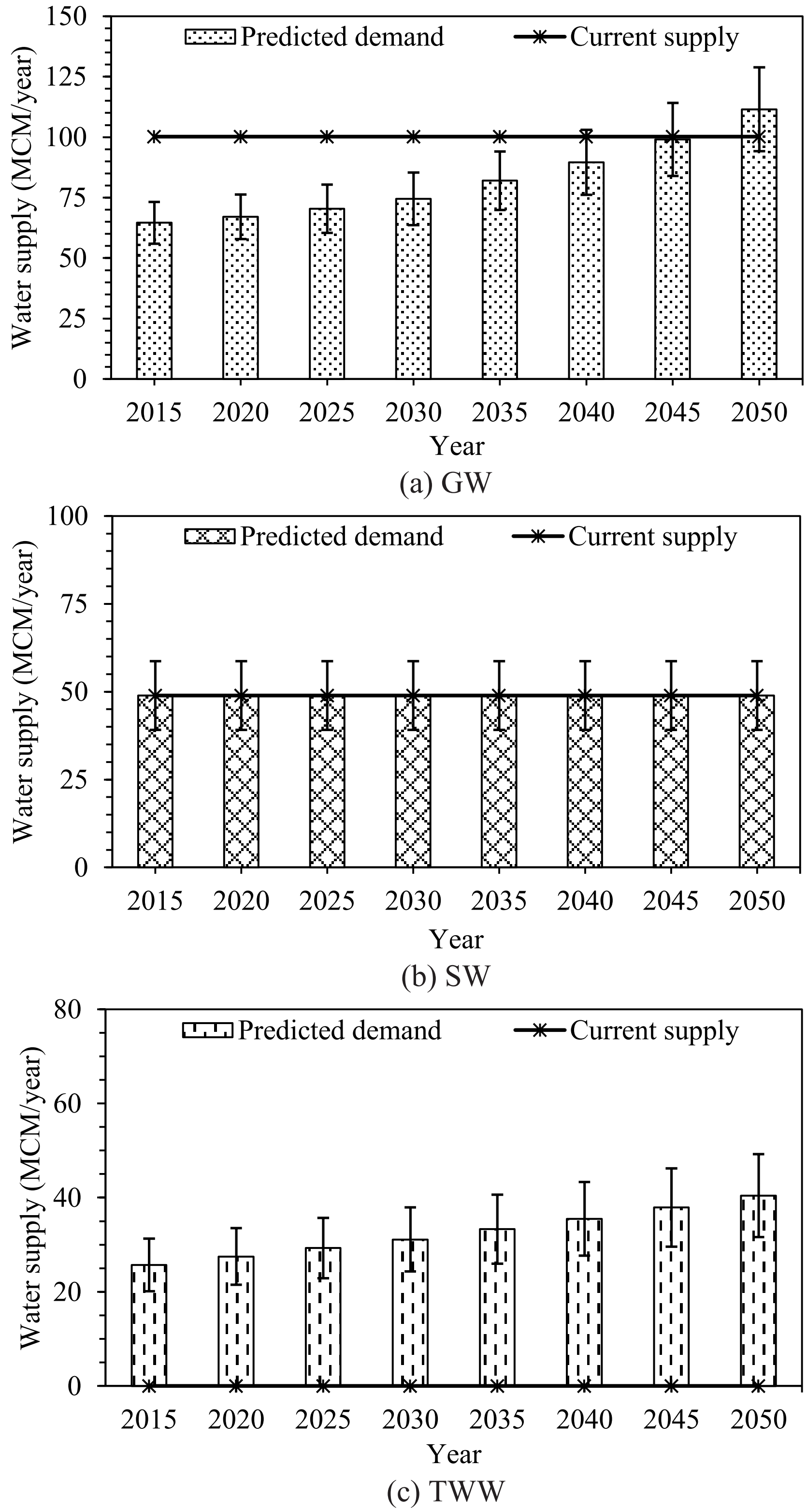


Figure 5.26: Predicted water demands from current supply sources in Al-Baha region.

Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of water from different sources are shown in Table 5.27. The current rate of GW withdrawal is likely to deliver the predicted quantities in full up to 2025, while in 2030, 2035, 2040, 2045 and 2050, there will be 1%, 5%, 22%, 50% and 73% chances of non-satisfying the predicted quantities in full respectively. The predicted quantities of TWW cannot be satisfied in any year.

Table 5.27: Probabilities of satisfying the predicted water from current supply sources in Al-Baha region (%).

Year \ Source	GW	SW	TWW
2015	100.0	100.0	0.0
2020	100.0	100.0	0.0
2025	100.0	100.0	0.0
2030	99.0	100.0	0.0
2035	95.0	100.0	0.0
2040	78.0	100.0	0.0
2045	50.0	100.0	0.0
2050	27.0	100.0	0.0

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

5.10.4 Cost of Water Supply

The average costs of using predicted water from different sources are presented in Figure 5.27. In 2015, the cost for supplying the predicted GW is 118.5 million SR, which is forecasted to be 205.1 million SR by 2050 (2.1% increase annually). The cost for supplying SW is likely to be 90 million SR annually. The cost for reusing TWW has been estimated to be 137.6 and 216.4 million SR in 2015 and 2050 respectively. Among three supply sources, TWW has the dominance of higher cost in all years. The total cost of using predicted water from different sources has been estimated to be 346.1 million SR in 2015, which is predicted to be 511.5 million US$SR in 2050 (1.4% increase per year).

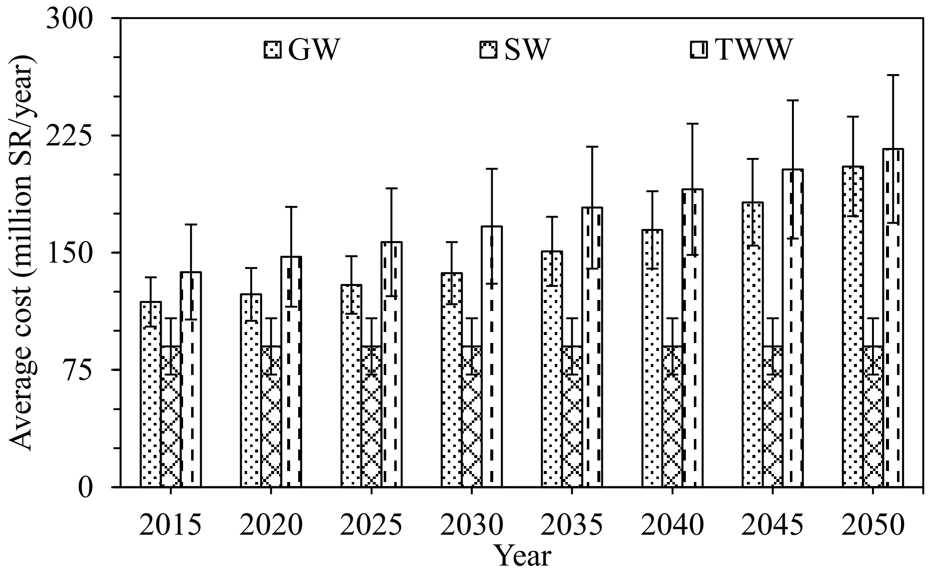
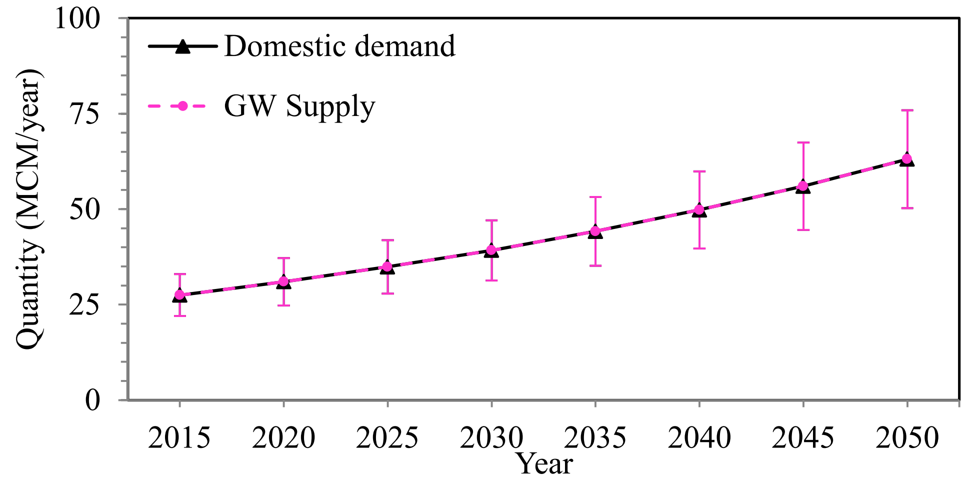


Figure 5.27: Average cost of supplying the predicted quantities of water from different sources in Al-Baha region: Mean (bars) and standard deviation (error bars).

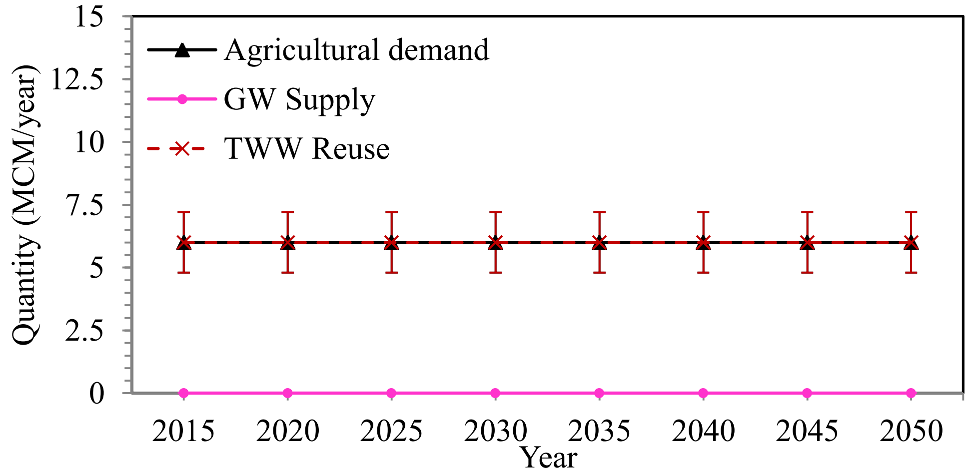
5.11 Northern Borders Region

5.11.1 Sector Wise Water Demands Satisfaction

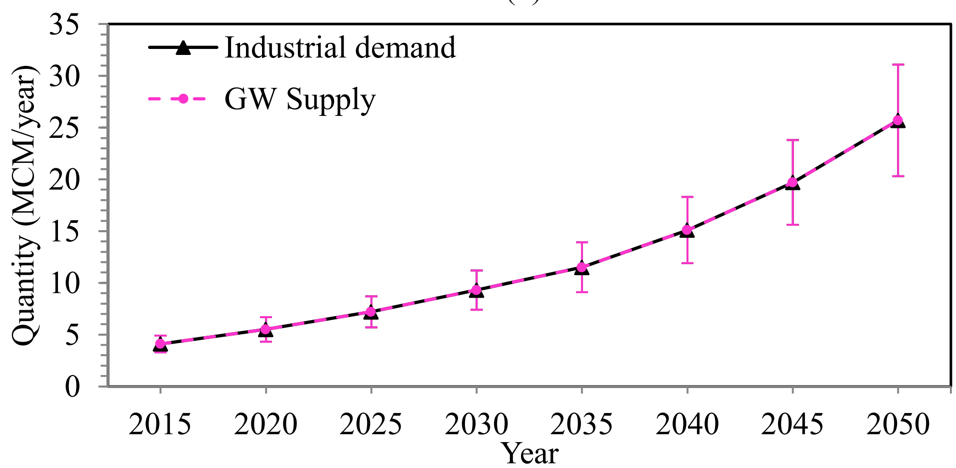
Figure 5.28 shows the satisfaction of sector wise water demands. Figure 5.28a indicates that the domestic water demand is likely to increase from 27.5 MCM in 2015 to 63.1 MCM in 2050, which is satisfied by GW. The agricultural water demand is 6.0 MCM/year, which can be satisfied by TWW (Figure 5.28b). The water demand in the industrial sector is predicted to increase from 4.1 MCM in 2015 to 25.7 MCM in 2050, which needs to be satisfied by GW (Figure 5.28c).



(a)



(b)



(c)

Figure 5.28: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Northern borders region: Mean (solid lines) and standard deviations (error bars).

Table 5.28 details the percentages of water contribution from various sources to the consumption sectors. The table indicates the full satisfaction of GW to domestic and industrial water demands, and TWW to agricultural water demands.

Table 5.28: Water supply contribution (%) from different sources to respective demand in Northern borders region.

Year	Domestic sector	Agricultural sector		Industrial sector
	GW	GW	TWW	GW
2015	100.0	0.0	100.0	100.0
2020	100.0	0.0	100.0	100.0
2025	100.0	0.0	100.0	100.0
2030	100.0	0.0	100.0	100.0
2035	100.0	0.0	100.0	100.0
2040	100.0	0.0	100.0	100.0
2045	100.0	0.0	100.0	100.0
2050	100.0	0.0	100.0	100.0

GW: Groundwater; TWW: Treated wastewater.

5.11.2 Water Quality Satisfaction

The TDS levels for various sectors from 2015 through 2050 are shown in Table 5.29. The TDS of water to be supplied from a single source for a specific purpose needs to be controlled at the supply source through treatment.

Table 5.29: Water quality achievement in terms of TDS (ppm) for various demand sectors in Northern borders region.

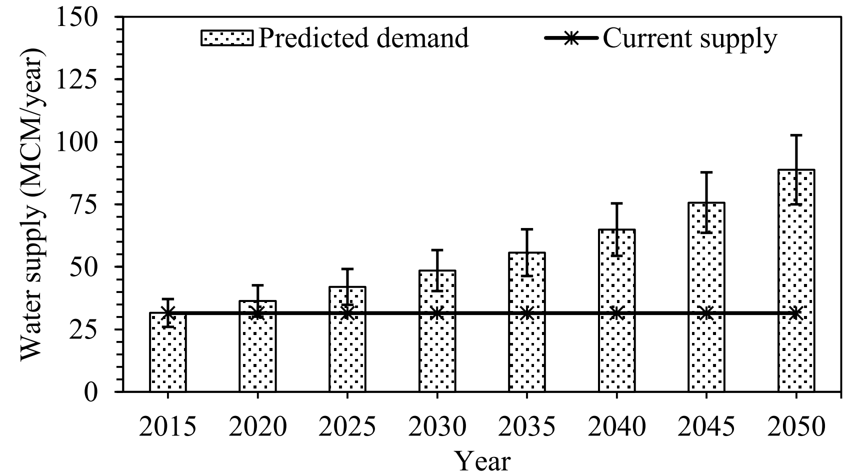
Year	Domestic sector	Agricultural sector		Industrial sector
	GW	GW	TWW	GW
2015	300	–	2000	300
2020	300	–	2000	300
2025	300	–	2000	300
2030	300	–	2000	300
2035	300	–	2000	300
2040	300	–	2000	300
2045	300	–	2000	300
2050	300	–	2000	300

GW: Groundwater; TWW: Treated wastewater.

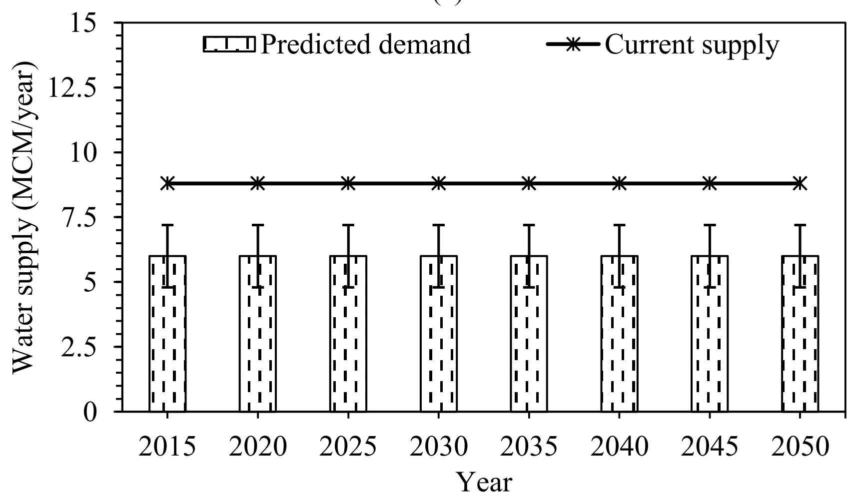
5.11.3 Source Wise Predicted Water Demands

Figure 5.29 shows the predicted quantities of water to be supplied from GW and TWW. The predicted withdrawal of GW is 31.6 MCM in 2015, which is likely to be 88.8 MCM in 2050 (Figure 5.29a). The generated wastewater was assumed to be equal to the predicted quantity of TWW. The domestic sector is expected to generate about 22 MCM of wastewater in 2015, which is expected to be 50.4 MCM in 2050. However, only 6 MCM/year of generated wastewater is needed as the predicted quantity, which is reused to fully satisfy agricultural water demand (Figure 5.29b).

The current rate of GW extraction showed negative deviations in all years, meaning that the objective to maximize GW conservation was not achieved. This means additional supply of GW is needed. Assuming the constant supply of GW of 31.5 MCM per year [21], there is a need to supply 31.6 MCM of GW in 2015, which is 0.1 MCM more than the current supply. Further, GW supply needs to be increased to 88.8 MCM by 2050, which is 57.3 MCM more than the current supply (Figure 5.29a). The current capacity of wastewater plants is approximately 8.8 MCM/year [21], while generation of domestic wastewater in 2015 is approximately 22 MCM and it is expected to be 50.4 MCM in 2050. However, from 2015-2050, only 6 MCM/year of TWW is needed as predicted quantity (Figure 5.29b). The current capacity of wastewater plants is adequate to fully satisfy the predicted TWW in all years (Figure 5.29b). The generated wastewater is higher than the treated and needed quantities. Reusing TWW in agricultural sectors needs to be maximized. Consequently, building infrastructures to collect and treat the generated wastewater in full is needed to maximize TWW for agricultural reuse.



(a) GW



(b) TWW

Figure 5.29: Predicted water demands from current supply sources in Northern borders region. Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of GW and TWW are shown in Table 5.30. The probability of satisfying the predicted GW in full is 46%, 23%, 6% and 2% in 2015, 2020, 2025 and 2030 respectively. Beyond 2030, the current supply of GW cannot satisfy any of the simulated 100 scenarios in any year. The current capacity of wastewater plants is likely to deliver the predicted TWW in all years.

Table 5.30: Probabilities of satisfying the predicted water from current supply sources in Northern borders region (%).

Year \ Source	GW	TWW
2015	46.0	100.0
2020	23.0	100.0
2025	6.0	100.0
2030	2.0	100.0
2035	0.0	100.0
2040	0.0	100.0
2045	0.0	100.0
2050	0.0	100.0

GW: Groundwater; TWW: Treated wastewater.

5.11.4 Cost of Water Supply

The costs of using water from different sources are shown in Figure 5.30. The cost of using GW is 58.1 million SR in 2015, which is estimated to be in 163.1 million SR in 2050. The cost for reusing TWW is likely to be 32.3 million SR annually. The total cost of using predicted water from different sources has been estimated to be 90.4 million SR in 2015, which is predicted to be 195.4 million SR in 2050.

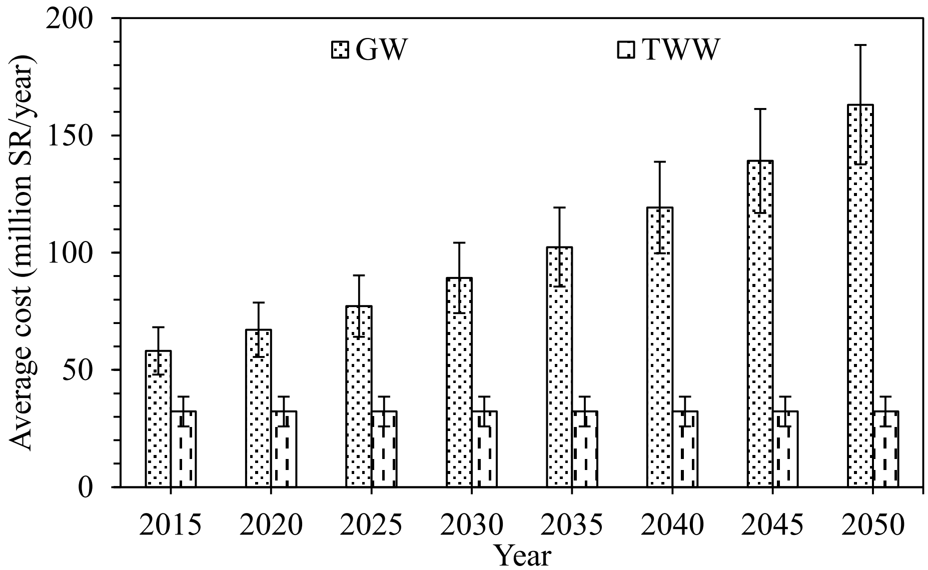


Figure 5.30: Average cost of supplying the predicted quantities of water from different sources in Northern borders region: Mean (bars) and standard deviation (error bars).

5.12 Al-Jouf Region

5.12.1 Sector Wise Water Demands Satisfaction

Figure 5.31 shows the satisfaction of sector wise water demands. Figure 5.31a indicates that the domestic water demand is likely to increase from 43.6 MCM in 2015 to 87.2 MCM in 2050, which is satisfied by GW. The agricultural water demand is 1196 MCM/year, which needs to be satisfied by GW and TWW. GW extraction for agriculture will be reduced from 1161.2 MCM in 2015 to 1126.4 MCM in 2050. TWW reuse in agricultural sector needs to be maximized from 34.8 MCM in 2015 to 69.6 MCM in 2050 (Figure 5.31b). The industrial water demand is predicted to increase from 13.9 MCM in 2015 to 89.1 MCM by 2050, which is satisfied by GW (Figure 5.31c).

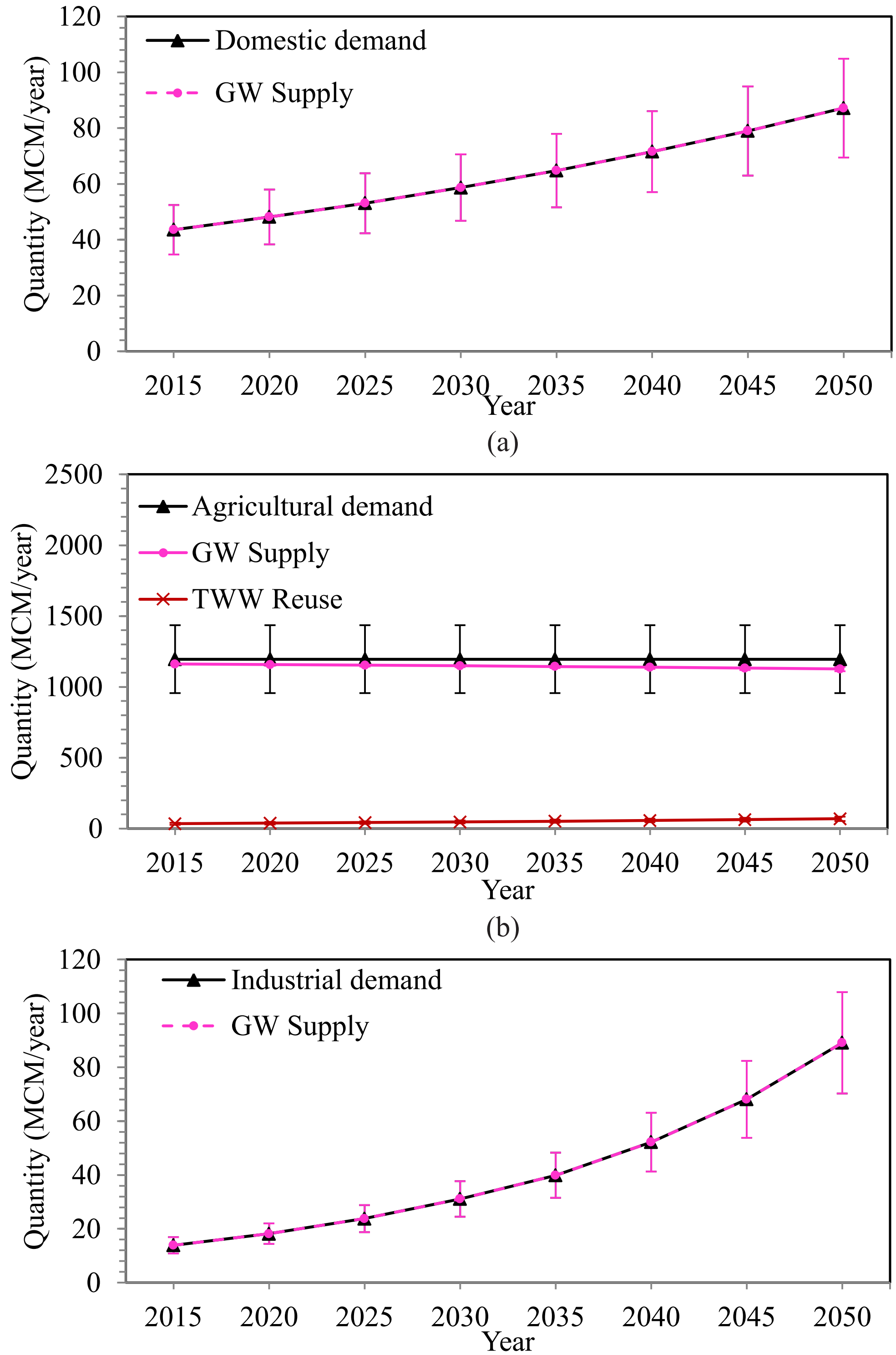


Figure 5.31: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Al-Jouf region: Mean (solid lines) and standard deviations (error bars).

Table 5.31 details the percentages of water contribution from various sources to the consumption sectors. The water demand in the domestic sector from 2015 through 2050 is satisfied by GW. The contribution of GW in the agriculture sector is estimated to reduce from 97.1% in 2015 to 94.2% in 2050 (2.9% reduction). TWW needs to satisfy 2.9% of agricultural water demand in 2015, and it is likely to be increased to 5.8% by 2050. The water demands in the industrial sector from 2015 through 2050 need to be satisfied by GW.

Table 5.31: Water supply contribution (%) from different sources to respective demand in Al-Jouf region.

Year	Domestic sector	Agricultural sector		Industrial sector
	GW	GW	TWW	GW
2015	100.0	97.1	2.9	100.0
2020	100.0	96.8	3.2	100.0
2025	100.0	96.5	3.5	100.0
2030	100.0	96.1	3.9	100.0
2035	100.0	95.7	4.3	100.0
2040	100.0	95.2	4.8	100.0
2045	100.0	94.7	5.3	100.0
2050	100.0	94.2	5.8	100.0

GW: Groundwater; TWW: Treated wastewater.

5.12.2 Water Quality Satisfaction

The TDS levels for various demand sectors from 2015 through 2050 are summarized in Table 5.32.

Table 5.32: Water quality achievement in terms of TDS (ppm) for various demand sectors in Al-Jouf region.

Year	Domestic sector	Agricultural sector		Industrial sector
	GW	GW	TWW	GW
2015	300	3500	2000	300
2020	300	3500	2000	300
2025	300	3500	2000	300
2030	300	3500	2000	300
2035	300	3500	2000	300
2040	300	3500	2000	300
2045	300	3500	2000	300
2050	300	3500	2000	300

GW: Groundwater; TWW: Treated wastewater.

5.12.3 Source Wise Predicted Water Demands

Figure 5.32 shows the predicted quantities of water to be supplied from GW and TWW. In 2015, water supplies are 1218.7 and 34.8 MCM of GW and TWW respectively, which is projected to increase to 1302.7 and 69.6 MCM respectively by 2050. Supply of GW and TWW needs to be increased to approximately 1.1 and 2.0 folds to the water in 2015 respectively (Figure 5.32a, b).

The current supply of GW showed positive deviations in all years, meaning that the objective to maximize GW conservation was achieved. The maximum extraction of GW is 1302.7 MCM in 2050, which can be satisfied by the current rate of GW withdrawal. Assuming the constant supply of GW of 1425.6 MCM per year [21], this source satisfies the demands from 2015 through 2050 (Figure 5.32a). The current capacity of wastewater plants is approximately 14.6 MCM/year [21], while generation of domestic wastewater in 2015 is approximately 34.8 MCM, which is 20.2 MCM more than the current capacity. In 2050, wastewater generation is expected to be 69.6 MCM, which is 55 MCM more than the current capacity (Figure 5.32b). Reuse of TWW in agricultural sectors needs to be maximized. Consequently, building infrastructures to collect and treat the domestic wastewater is needed in order to maximize TWW for agricultural reuse.

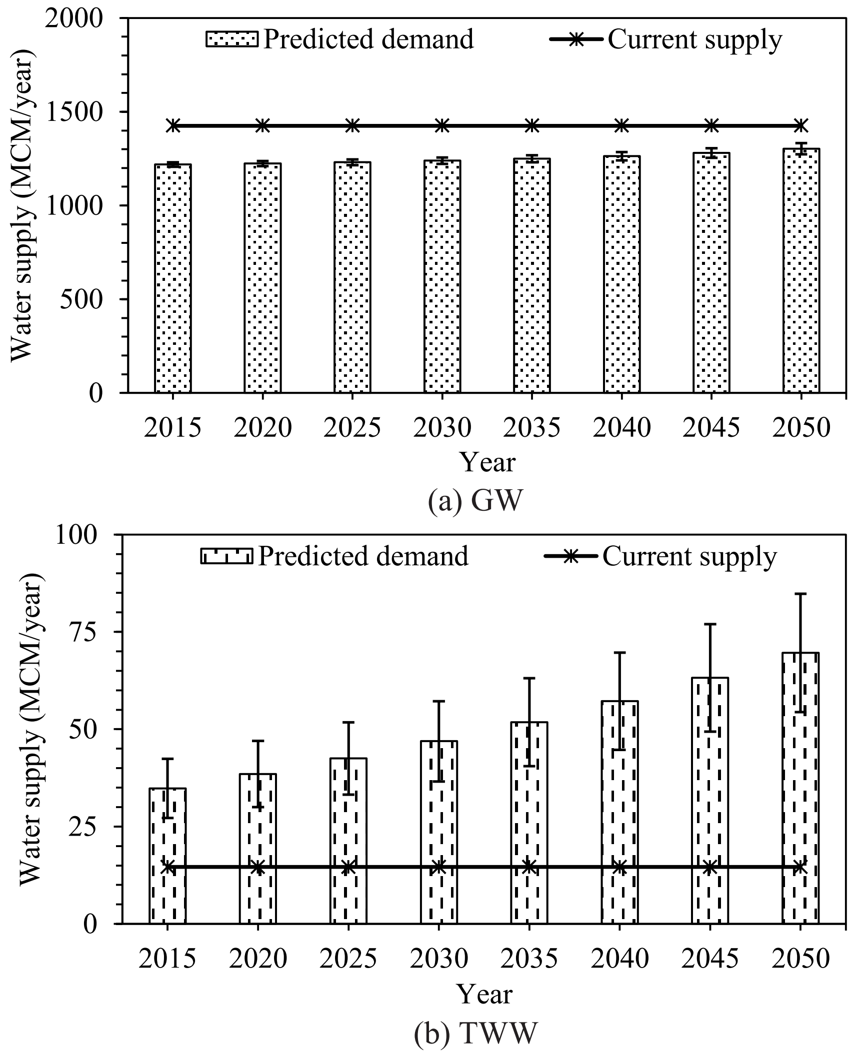


Figure 5.32: Predicted water demands from current supply sources in Al-Jouf region. Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of GW and TWW are shown in Table 5.33. The current rate of GW withdrawal is likely to deliver the predicted quantities from 2015 through 2050. During this period, the current capacity of wastewater plants cannot fully satisfy any of the 100 random scenarios assessed in this study.

Table 5.33: Probabilities of satisfying the predicted water from current supply sources in AL-Jouf region (%).

Source / Year	GW	TWW
2015	100.0	0.0
2020	100.0	0.0
2025	100.0	0.0
2030	100.0	0.0
2035	100.0	0.0
2040	100.0	0.0
2045	100.0	0.0
2050	100.0	0.0

GW: Groundwater; TWW: Treated wastewater.

5.12.4 Cost of Water Supply

The average costs of using water from different sources are presented in Figure 5.33. The costs of using GW and TWW in 2015 are approximately 2239.5 and 186.8 million SR respectively. In 2050, these costs have been estimated to be 2393.6 and 373.5million SR respectively. The total cost of using water from different sources has been estimated to be 2.4 billion SR in 2015, which is predicted to be 2.8 billion SR in 2050.

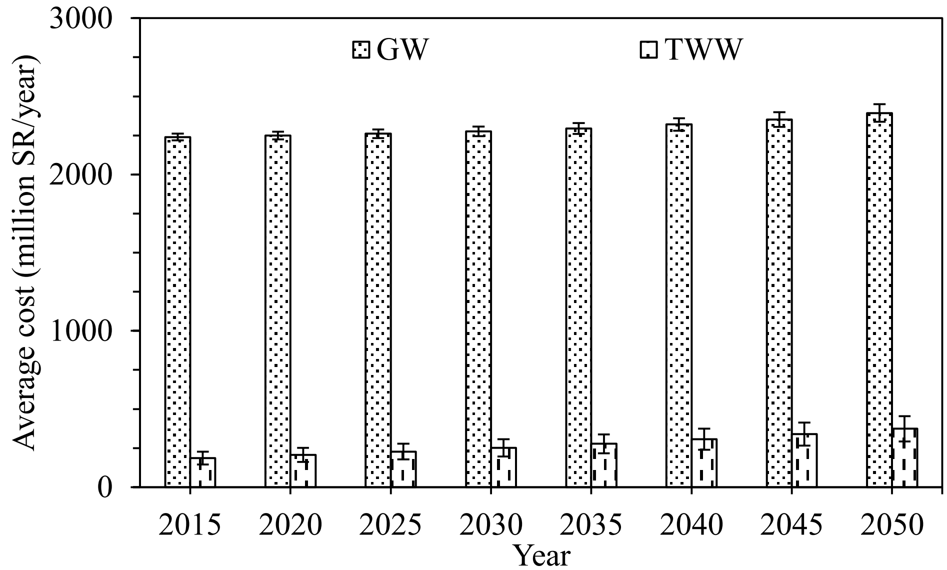


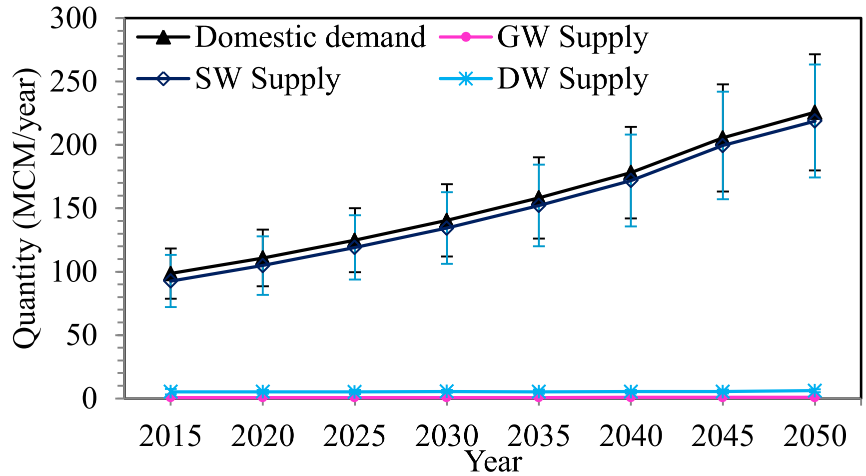
Figure 5.33: Average cost of supplying the predicted quantities of water from different sources in Al-Jouf region: Mean (bars) and standard deviation (error bars).

5.13 Jazan Region

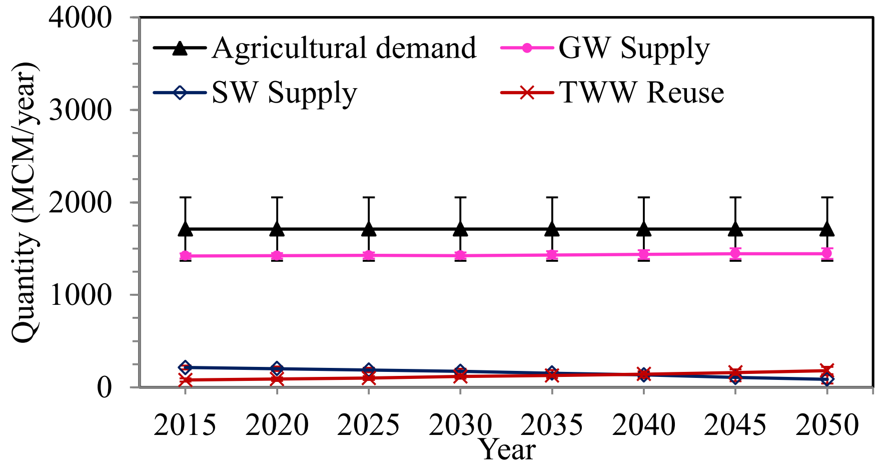
5.13.1 Sector Wise Water Demands Satisfaction

Figure 5.34 shows the water demands in domestic, agricultural and industrial sectors and the predicted supplies from different sources. The domestic water demand is satisfied by GW, SW and DW. In 2015, domestic water demand is 98.5 MCM, which is anticipated to be 225.8 MCM in 2050 (Figure 5.34a). From 2015 through 2050, GW, SW and DW supplies are forecasted to increase from 0.7, 92.6 and 5.3 MCM to 0.9, 218.9 and 6.1 MCM respectively (Figure 5.34a). The agricultural water demand is 1712 MCM/year, which is satisfied by GW, SW and TWW. GW extraction for agriculture is estimated to increase from 1420.2 MCM in 2015 to 1444.8 MCM by 2050. In this period, TWW reuse for agriculture is estimated to increase from 78.8 MCM to 180.4 MCM.

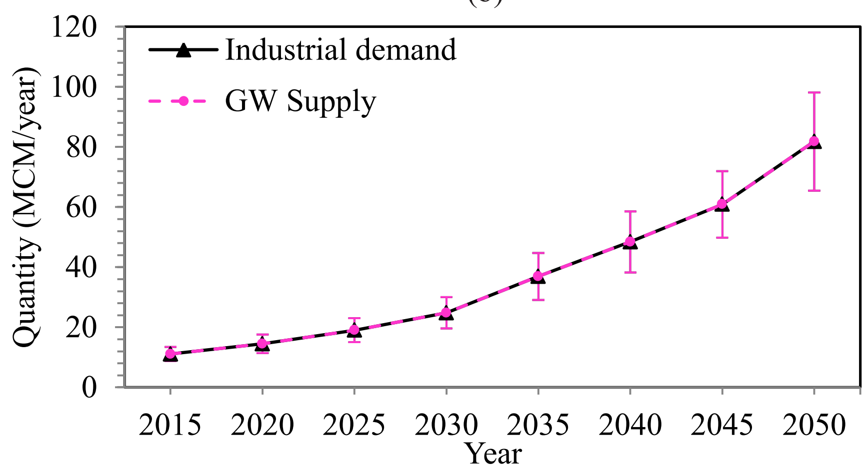
SW supply to agricultural sector may gradually decrease from 213 MCM in 2015 to 86.7 MCM in 2050 (Figure 5.34b). Water demand in industrial sector needs to be satisfied by GW, which will be increased from 11.1 MCM in 2015 to 81.8 MCM by 2050 (Figure 5.34c).



(a)



(b)



(c)

Figure 5.34: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Jazan region: Mean (solid line) and standard deviations (error bars).

The water contributions from multiple sources to multiple sectors are given in Table 5.34. Approximately 0.7%, 93.6% and 5.7% of domestic water demand in 2015 is likely to be satisfied by GW, SW and DW respectively. In 2050, these proportions are observed to be 0.4%, 96.9% and 2.7% respectively. It is to be noted that the contribution of SW in domestic sector from 2015 through 2050 is expected to have an increase of approximately 3.3%, while GW and DW contribution may have a reduction of approximately 0.3% and 3.0% respectively. From 2015 to 2050, contribution of GW and TWW reuse to agriculture may increase from 83.0% and 4.6% to 84.6% and 10.4% respectively. During this period, SW contribution in agricultural sector is expected to decrease from 12.4% to 5.0%. Water demands in industrial sector from 2015 through 2050 will be fully satisfied by GW supply.

Table 5.34: Water supply contribution (%) from different sources to respective demand in Jazan region.

Year	Domestic sector			Agricultural sector			Industrial sector
	GW	SW	DW	GW	SW	TWW	GW
2015	0.7	93.6	5.7	83.0	12.4	4.6	100.0
2020	0.7	94.3	5.0	83.1	11.7	5.2	100.0
2025	0.6	95.1	4.3	83.3	10.9	5.8	100.0
2030	0.5	95.4	4.1	83.2	10.0	6.8	100.0
2035	0.5	96.0	3.5	83.7	9.0	7.3	100.0
2040	0.5	96.3	3.2	83.9	7.8	8.3	100.0
2045	0.4	96.9	2.7	84.5	6.2	9.3	100.0
2050	0.4	96.9	2.7	84.6	5.0	10.4	100.0

GW: Groundwater; SW: Surface water; DW: Desalinated water TWW: Treated wastewater.

5.13.2 Water Quality Satisfaction

The water qualities from 2015 through 2050 are shown in Table 5.35. The target TDS for each sector was satisfied. In domestic sector, the TDS for blended water in 2015 is 408.8 ppm, which will be 442.8 ppm in 2050.

Table 5.35: Water quality achievement in terms of TDS (ppm) for various demand sectors in Jazan region.

Year	Domestic sector		Agricultural sector			Industrial sector
	Blended water (GW + DW)	SW	GW	SW	TWW	GW
2015	408.8	225	3500	225	2000	300
2020	408.9	225	3500	225	2000	300
2025	408.3	225	3500	225	2000	300
2030	405.0	225	3500	225	2000	300
2035	426.1	225	3500	225	2000	300
2040	448.3	225	3500	225	2000	300
2045	439.7	225	3500	225	2000	300
2050	442.8	225	3500	225	2000	300

GW: Groundwater; SW: Surface water; DW: Desalinated water TWW: Treated wastewater.

5.13.3 Source Wise Predicted Water Demands

Figure 5.35 presents the predicted amounts of water to be supplied from various sources for the period of 2015-2050. Extraction of GW is expected to be increased from 1432 MCM in 2015 to 1527.5 MCM in 2050 (Figure 5.35a). The available SW (305.6 MCM/year) was fully allocated for satisfying water demands in domestic and agricultural sectors (Figure 5.35b). In case of DW, about 5.3 MCM is needed in 2015, which is estimated to be 6.1 MCM in 2050 (Figure 5.35c). In 2015, domestic sector is expected to generate about 78.8 MCM of wastewater, which is likely to increase to 180.4 MCM in 2050 (Figure 5.35d).

With reference to water availability, the current supply of GW, SW, DW and TWW was 1689.7, 305.6, 6 and 7.5 MCM per year respectively [21]. There is no need to extract additional water beyond the present GW supply from 2015 to 2050, meaning that the priority to minimize GW extraction (R_9) was achieved (Figure 5.35a). The priority to maximize SW use (R_8) was achieved, showing the full allocation of SW in all years (Figure 5.35b). In case of TWW, current capacity of sewage plants is not adequate to fully treat the generated wastewater in all years (Figure 5.35d). Presently, only 7.3 MCM/year of wastewater is being treated, while only 4.1 MCM/year of TWW is recycled for reuse [21]. Reuse of TWW in agricultural sectors needs to be maximized.

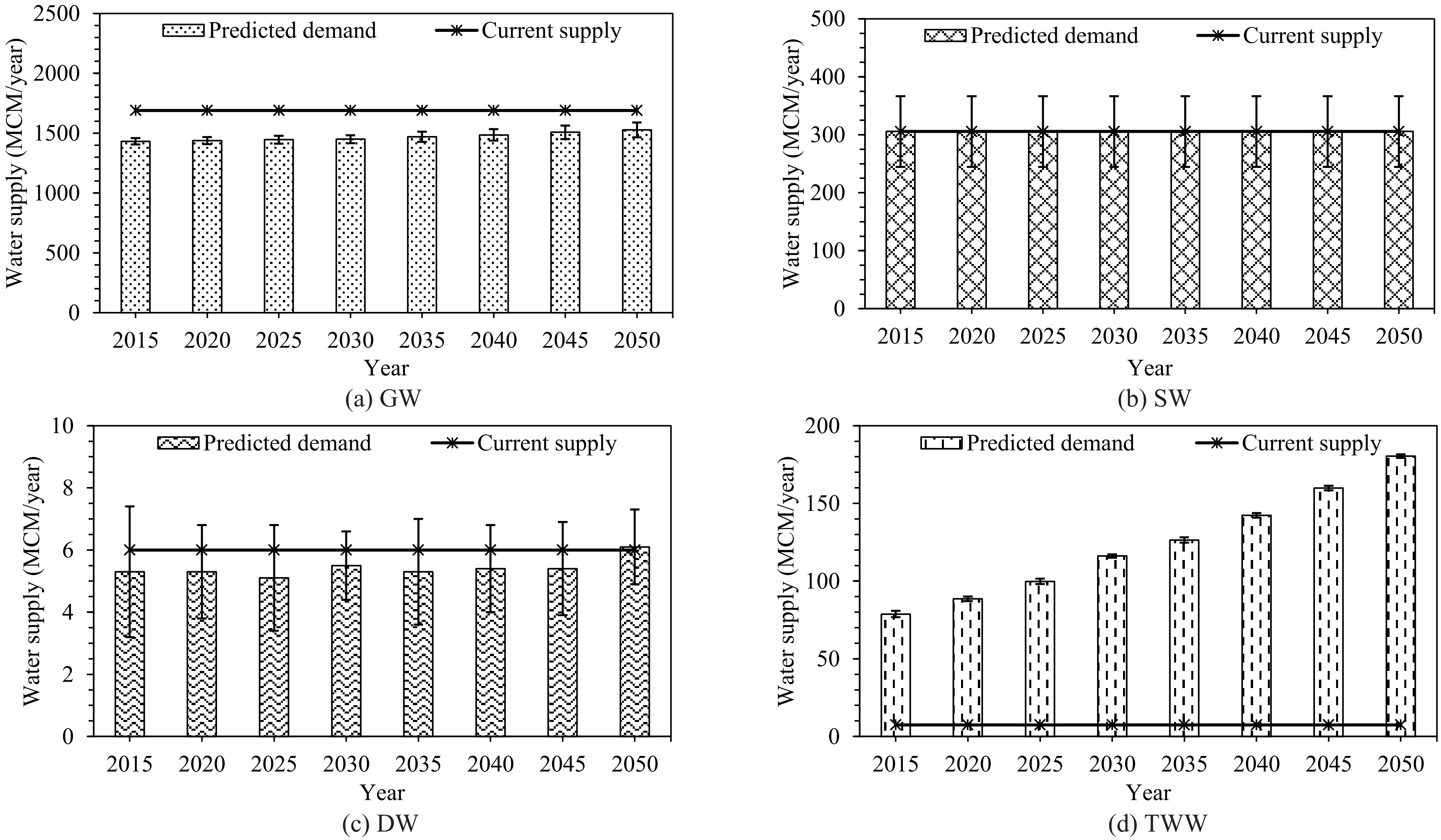


Figure 5.35: Predicted water demands from current supply sources in Jazan region. Error bars represent the standard deviations.

The current rate of GW extraction is likely to satisfy the predicted quantities till 2045; while in 2050, the probability of satisfying the predicted GW is expected to be 99% (Table 5.36). The probability of satisfying the predicted quantity of DW by the current supply is expected to decrease from 84% in 2015 to 74% by 2050. From 2015-2050, the current capacity of wastewater plants cannot fully satisfy any of the 100 random scenarios assessed in this study.

Table 5.36: Probabilities of satisfying the predicted water from current supply sources in Jazan region (%).

Source / Year	GW	SW	DW	TWW
2015	100.0	100.0	84.0	0.0
2020	100.0	100.0	79.0	0.0
2025	100.0	100.0	82.0	0.0
2030	100.0	100.0	79.0	0.0
2035	100.0	100.0	80.0	0.0
2040	100.0	100.0	83.0	0.0
2045	100.0	100.0	83.0	0.0
2050	99.0	100.0	74.0	0.0

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater.

5.13.4 Cost of Water Supply

The costs of using water from different sources have been summarized in Figure 5.36. The cost for supplying the predicted quantity of GW may increase from 2631.4 million SR in 2015 to 2806.9 million SR in 2050. The cost for supplying SW is likely to be 561.4 million SR annually. Supplying the predicted quantity of DW in 2015 is expected to cost 36.4 million SR, which is forecasted to be to 42 million SR by 2050. In 2015, the cost for reusing TWW was estimated to be 422.3 million SR, which will increase to 967.5 million SR in 2050. The total cost of using water from different sources has been estimated to be

3.7 billion SR in 2015, which may increase to 4.4 billion SR in 2050 (approximately 0.6% increase per year).

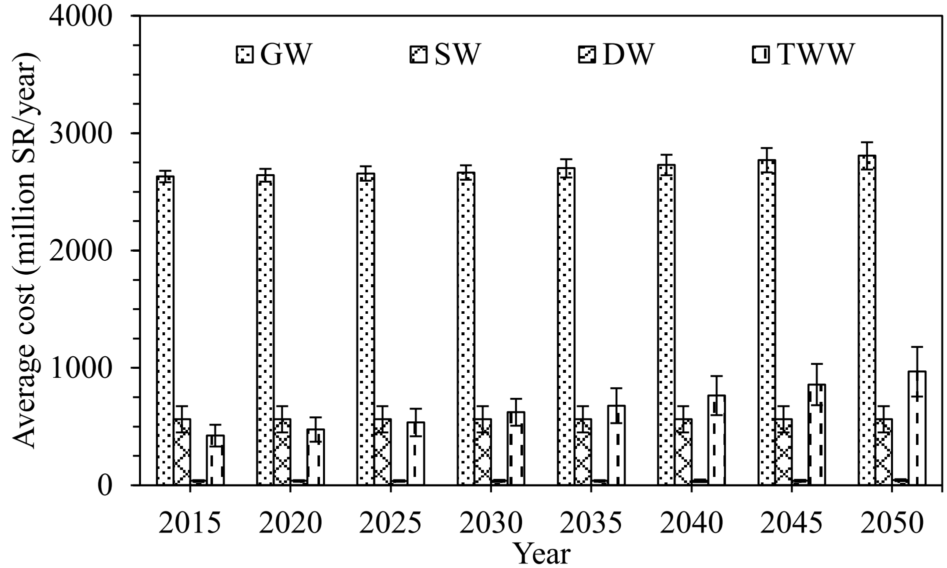


Figure 5.36: Average cost of supplying the predicted quantities of water from different sources in Jazan region: Mean (bars) and standard deviation (error bars).

5.14 Najran Region

5.14.1 Sector Wise Water Demands Satisfaction

Figure 5.37 shows the satisfaction of sector wise water demands. Figure 5.37a indicates that the domestic water demand in 2015 is 42.9 MCM, which is satisfied by GW (42.6 MCM) and SW (0.3 MCM). In 2050, supply of GW and SW in domestic sector is likely to be 105 and 0.3 MCM respectively. For agriculture, GW extraction will be reduced from 172.7 MCM in 2015 to 122.9 MCM in 2050 (Figure 5.37b). TWW reuse in agricultural sector needs to be maximized from 34.3 MCM in 2015 to 84.1 MCM in 2050 (Figure 5.37b). The industrial water demand is predicted to increase from 7 MCM in 2015 to 51.2 MCM by 2050, which is satisfied by GW (Figure 5.37c).

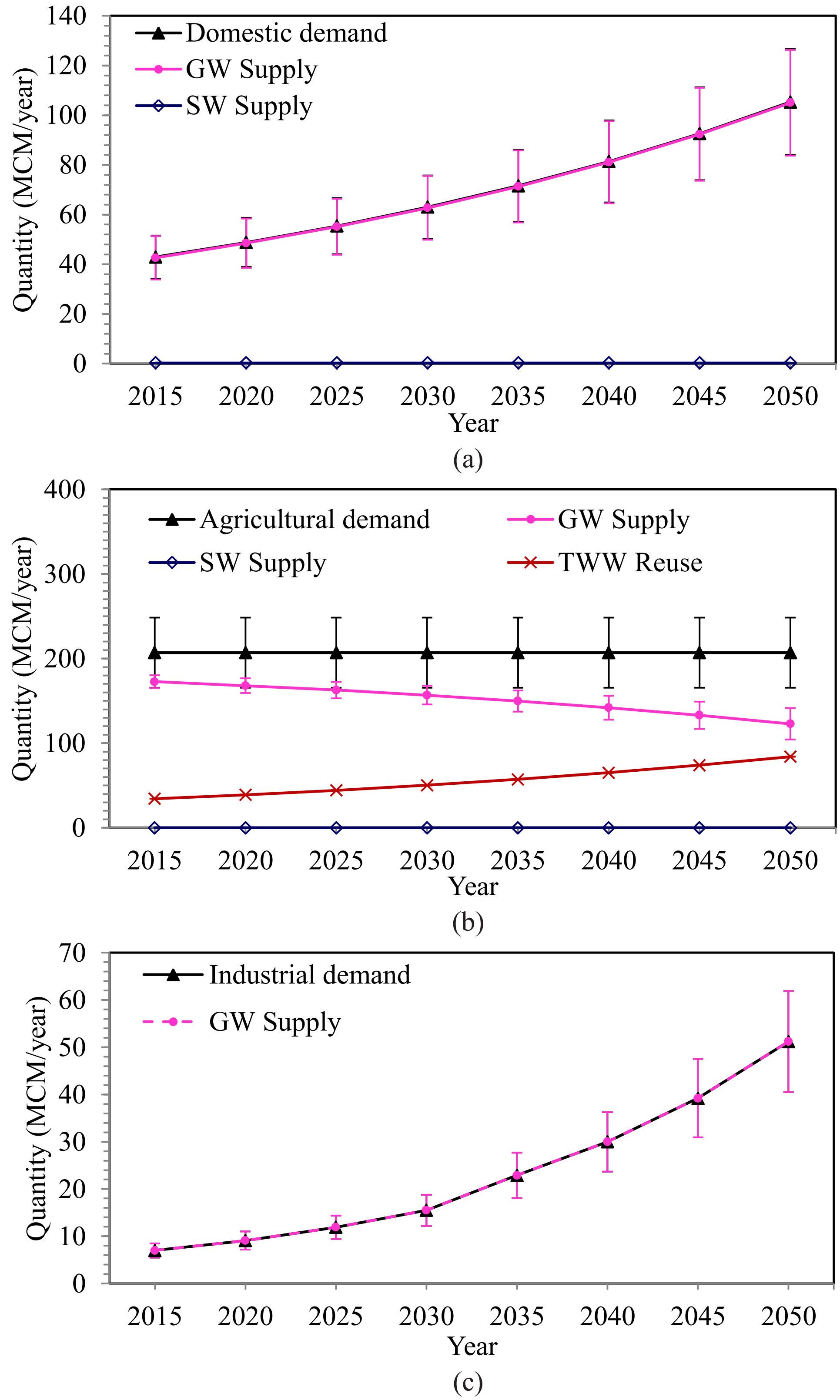


Figure 5.37: Source wise water needed for (a) domestic, (b) agricultural and (c) industrial sectors in Najran region: Mean (solid line) and standard deviations (error bars).

Table 5.37 shows the percentages of water contribution from various sources to the consumption sectors. From 2015-2050, GW contribution in domestic sectors is expected to increase from 99.3% to 99.7%. During this period, SW contribution in domestic sector is likely to decrease from 0.7% in 2015 to 0.3% in 2050. The contribution of GW to agriculture sector is estimated to reduce from 83.4% in 2015 to 59.4 % in 2050 (24% reduction). TWW needs to satisfy 16.6% of agricultural water demand in 2015, and it is likely to be increased to 40.6% by 2050. The water demand in the industrial sector from 2015 through 2050 needs to be fully satisfied by GW.

Table 5.37: Water supply contribution (%) from different sources to respective demand in Najran region.

Year	Domestic sector		Agricultural sector			Industrial sector
	GW	SW	GW	SW	TWW	GW
2015	99.3	0.7	83.4	0.0	16.6	100.0
2020	99.4	0.6	81.2	0.0	18.8	100.0
2025	99.4	0.6	78.6	0.0	21.4	100.0
2030	99.5	0.5	75.7	0.0	24.3	100.0
2035	99.6	0.4	72.4	0.0	27.6	100.0
2040	99.6	0.4	68.6	0.0	31.4	100.0
2045	99.7	0.3	64.3	0.0	35.7	100.0
2050	99.7	0.3	59.4	0.0	40.6	100.0

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

5.14.2 Water Quality Satisfaction

The TDS levels for various sectors from 2015 through 2050 are shown in Table 5.38.

Table 5.38: Water quality achievement in terms of TDS (ppm) for various demand sectors in Najran region.

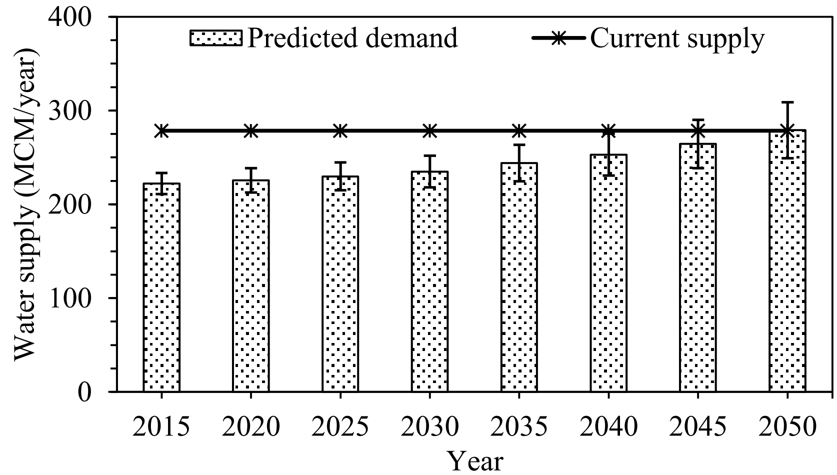
Year	Domestic sector		Agricultural sector			Industrial sector
	GW	SW	GW	SW	TWW	GW
2015	300	225	3500	–	2000	300
2020	300	225	3500	–	2000	300
2025	300	225	3500	–	2000	300
2030	300	225	3500	–	2000	300
2035	300	225	3500	–	2000	300
2040	300	225	3500	–	2000	300
2045	300	225	3500	–	2000	300
2050	300	225	3500	–	2000	300

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

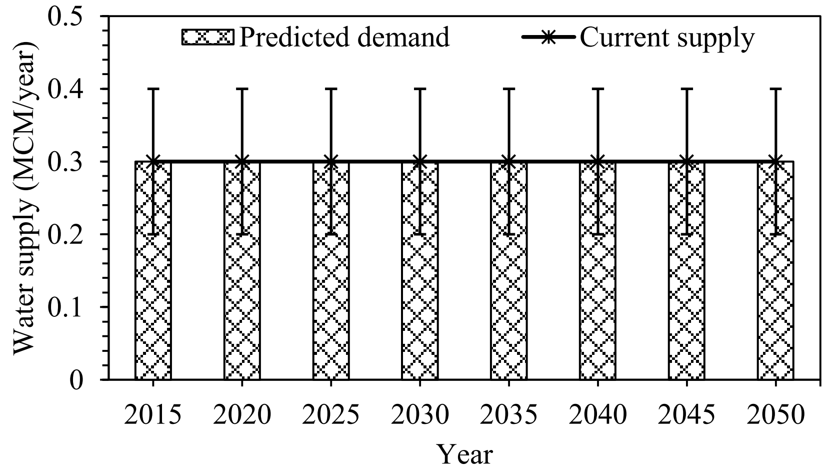
5.14.3 Source Wise Predicted Water Demands

Figure 5.38 shows the predicted amounts of water to be supplied from GW, SW and TWW. In 2015, water supplies are 222.2, 0.3 and 34.3 MCM of GW, SW and TWW respectively, which are projected to be 279, 0.3 and 84.1 MCM respectively by 2050. Supply of GW and TWW needs to be increased to approximately 1.3 and 2.5 folds to the water in 2015 respectively (Figure 5.38a, c).

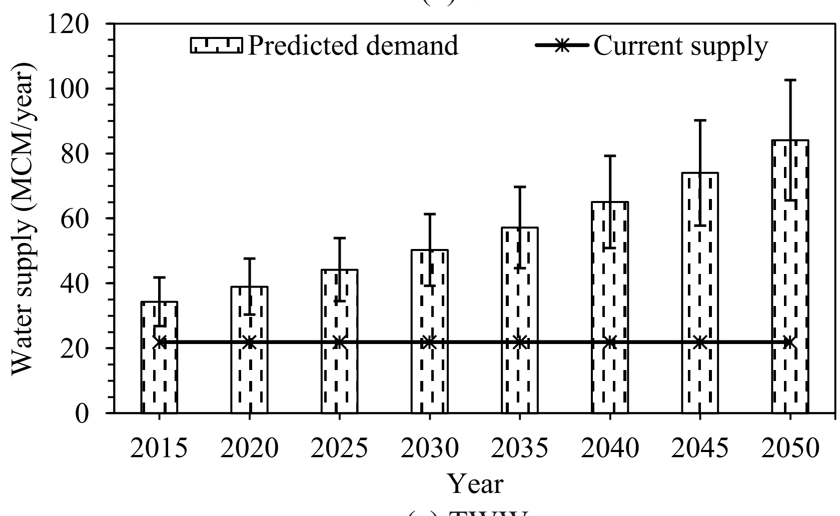
Assuming the constant supply of GW of 278.4 MCM per year [21], this source satisfies the demands till 2045 (Figure 5.38a). In 2050, the extraction of GW is 279 MCM, which is 0.6 MCM more than the current rate of GW withdrawal. The current supply of SW (0.3 MCM/year) was fully allocated for satisfying water demands in domestic sector (Figure 5.38b). The current capacity of wastewater plants is approximately 21.9 MCM/year [21], while generation of domestic wastewater in 2015 is approximately 34.3 MCM, which is 12.4 MCM more than the current capacity, and it is expected to be 84.1 MCM in 2050, which is 62.2 MCM more than the current capacity (Figure 5.38c). Reuse of TWW in agricultural sectors needs to be maximized. Consequently, building infrastructures to collect and treat the domestic wastewater is needed to maximize TWW reuse in agriculture.



(a) GW



(b) SW



(c) TWW

Figure 5.38: Predicted water demands from current supply sources in Najran region.

Error bars represent the standard deviations.

The probabilities of satisfying the predicted quantities of water from different sources are shown in Table 5.39. The current rate of GW withdrawal is likely to deliver the predicted quantities till 2025, while in 2030, 2035, 2040, 2045 and 2050, there will be 1%, 4%, 10%, 35% and 54% chances of non-satisfying the predicted quantities in full respectively. The existing wastewater plants may satisfy TWW demands in 4%, 1% and 1% cases in 2015, 2020 and 2025 respectively. Beyond 2025, the current capacity of these plants cannot fully satisfy any of the 100 random scenarios assessed in this study.

Table 5.39: Probabilities of satisfying the predicted water from current supply sources in Najran region (%).

Year \ Source	GW	SW	TWW
2015	100.0	100.0	4.0
2020	100.0	100.0	1.0
2025	100.0	100.0	1.0
2030	99.0	100.0	0.0
2035	96.0	100.0	0.0
2040	90.0	100.0	0.0
2045	65.0	100.0	0.0
2050	46.0	100.0	0.0

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

5.14.4 Cost of Water Supply

The average costs of using predicted water from different sources are presented in Figure 5.39. In 2015, the cost for supplying the predicted quantity of GW is 408.4 million SR, which is predicted to be 512.6 million SR by 2050 (0.7% increase per year). The cost for supplying SW is likely to be 0.4 million SR annually. The cost for reusing TWW has been estimated to be 184.1 in 2015 and 451.1 million SR in 2050. The total cost of using predicted water from different sources has been estimated to be 592.9 million SR in 2015, which is predicted to be 964.1 million SR in 2050 (1.8% increase per year).

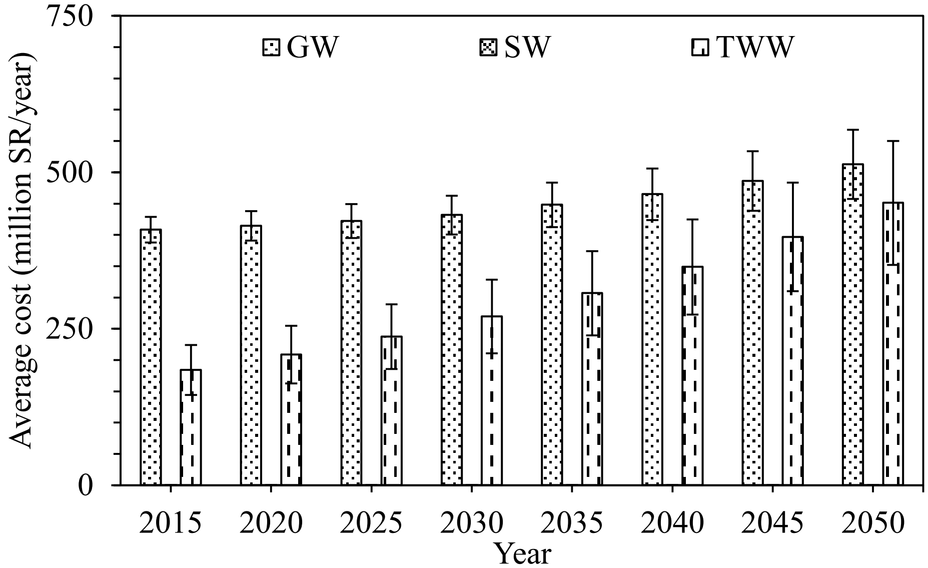


Figure 5.39: Average cost of supplying the predicted quantities of water from different sources in Najran region: Mean (bars) and standard deviation (error bars).

5.15 Comparison of Results

5.15.1 Sector Wise Water Demands Satisfaction

5.15.1.1 Domestic Water Demands

Table 5.40 shows the region wise total domestic water demands and the source wise distributions necessary to satisfy the demands for the period of 2015 through 2050. Among the 13 regions, domestic water demands were highest in Riyadh followed by Makkah and Eastern region. In 2015, domestic water demands in Riyadh, Makkah and Eastern region were estimated to be 761.6, 676 and 392.5 MCM respectively, which is projected to be 1658.1, 1306.2 and 758.4 MCM respectively in 2050. Domestic water demands were lowest in the Northern borders (2015) and Al-Baha (2050). The total domestic water demand in Saudi Arabia is forecasted to increase from 2625.2 MCM in 2015 to 5429.2 MCM by 2050 (approximately 3.1% increase annually). Approximately 29-30.5%, 24.1-25.8% and 14-15% of the domestic demands are attributed by Riyadh, Makkah and Eastern region respectively.

From 2015 through 2050, the highest extraction of GW for domestic purpose is required for Riyadh, while in 2050; Riyadh, Hail and Najran need almost the same amount of GW extraction. In 2015, the largest withdrawal of GW was 99.3 MCM in Riyadh, which is likely to increase to 166.2 MCM in 2040. From 2015 through 2040, withdrawal of GW to domestic sector in Saudi Arabia may be increased by 8 MCM/year (from 458.1 in 2015 to 658.1 MCM in 2040), indicating an increase of approximately 1.7% per year. In 2045 and 2050, the GW withdrawals are likely to be reduced to 621 and 585.3 MCM respectively, possible due to contributions from DW. SW is available in 5 out of 13 regions: Makkah, Aseer, Al-Baha, Jazan and Najran. In 2015, withdrawal of SW for domestic sector ranges from 0.3 MCM in Najran to 92.6 MCM in Jazan. The total SW withdrawal in 2015 is 207.7 MCM, which is likely to increase to 349.1 MCM in 2050. Supply of DW is needed to increase at the rate of 3.3-4.2% per year in all regions receiving DW (except Jazan). The minimum and maximum supply of DW is needed in Jazan and Riyadh respectively, with the quantities of 5.1-6.1 MCM and 662.3-1553.6 MCM respectively. In 2015, total supply of DW in the country is projected to be 1959.4 MCM, which is likely to increase to 4494.8 MCM in 2050 (approximately 3.7% increase per year).

Table 5.40: Source wise water needed for domestic sectors in the regions of Saudi Arabia (MCM/year).

Year	Demand / Supply	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	Demand	761.6	676	187.6	97.3	392.5	138.6	50.6	76.2	32.2	27.5	43.6	98.6	42.9	2625.2
	GW	99.3	83.1	24.5	12.7	51.2	12.4	50.6	9.9	0	27.5	43.6	0.7	42.6	458.1
	SW		38.8				43.8			32.2			92.6	0.3	207.7
	DW	662.3	554.1	163.1	84.6	341.3	82.4		66.3				5.3		1959.4
2020	Demand	849.1	742.7	207.9	108.6	431.1	153.1	57.1	85.4	34.4	31	48.2	110.9	48.8	2908.3
	GW	110.7	89.5	27.1	14.2	56.2	14.1	57.1	11.1	0	31	48.2	0.7	48.5	508.4
	SW		41.3				44.8			34.4			104.9	0.3	225.7
	DW	738.4	611.9	180.8	94.4	374.9	94.2		74.3				5.3		2174.2
2025	Demand	946.7	816	235.1	121	473.6	169	62.4	95.7	36.6	34.9	53.1	124.9	55.4	3224.4
	GW	123.5	97.1	30.7	15.8	54.1	16.1	62.4	12.4	0.2	34.9	53.1	0.7	55.1	556.1
	SW		43.6				45.3			36.4			119.1	0.3	244.7
	DW	823.2	675.3	204.4	105.2	419.5	107.6		83.3				5.1		2423.6
2030	Demand	1055.5	896.3	258.2	132.6	520.5	186.6	69.1	107.2	39	39.2	58.7	140.6	63	3566.5
	GW	137.7	109.9	33.7	17.2	43.4	18.4	69.1	13.9	0.5	39.2	58.7	0.7	62.7	605.1
	SW		42.9				45.5			38.5			134.4	0.3	261.6
	DW	917.8	743.5	224.5	115.4	477.1	122.7		93.3				5.5		2699.8
2035	Demand	1184.6	1009.5	298	151.6	571.8	206.1	76.7	120.1	41.7	44.2	64.8	158.2	71.6	3998.9
	GW	154.5	120.5	38.9	19.7	27.9	20.9	76.7	15.6	1.0	44.2	64.8	0.7	71.3	656.7
	SW		40.7				45.7			40.7			152.2	0.3	279.6
	DW	1030.1	848.3	259.1	131.9	543.9	139.5		104.5				5.3		3062.6
2040	Demand	1312.1	1082.2	327.3	171.8	628.3	227.5	85.1	134.7	44.5	49.8	71.6	178.1	81.4	4394.4
	GW	166.2	84.9	42.1	22.3	11.2	23.7	85.1	17.5	1.8	49.8	71.6	0.8	81.1	658.1
	SW		38				45.7			42.7			171.9	0.3	298.6
	DW	1145.9	959.3	285.2	149.5	617.1	158.1		117.2				5.4		3437.7
2045	Demand	1462.9	1188.9	368.5	186.9	690.3	251.1	94.4	150.8	47.5	56	79	205.7	92.6	4874.6
	GW	148.2	34.6	39.9	24.3	2.0	26.8	94.4	19.6	3.1	56	79	0.8	92.3	621
	SW		38.5				45.6			44.4			199.5	0.3	328.3
	DW	1314.7	1115.8	328.6	162.6	688.3	178.7		131.2				5.4		3925.3
2050	Demand	1658.1	1306.2	414.9	208.4	758.4	277.4	104.8	169	50.5	63.1	87.2	225.9	105.3	5429.2
	GW	104.5	3.0	32.5	27.1	0	30.4	104.8	22	4.8	63.1	87.2	0.9	105	585.3
	SW		40.3				43.9			45.7			218.9	0.3	349.1
	DW	1553.6	1262.9	382.4	181.3	758.4	203.1		147				6.1		4494.8

GW: Groundwater; SW: Surface water; DW: Desalinated water.

5.15.1.2 Agricultural Water Demands

Table 5.41 presents the agricultural water demands and necessary contributions from GW, SW and TWW for the period of 2015-2050. The maximum agricultural water demand is attributed by Riyadh (3467 MCM/year), while the minimum is for the Northern borders (6 MCM/year). The total water demand in agricultural sectors has been estimated to be 12794 MCM/year, in which approximately 55.1% is required for three regions: Riyadh (27.1%), Qaseem (14.6%) and Jazan (13.4%). It is to be noted that the agricultural water demand in Al-Jouf is approximately 9.3% of the total agricultural water consumption in the country, while Al-Jouf is the main producer of wheat in the country.

GW supply for agriculture shows decreasing trends in most of the regions. In Jazan, GW extraction may be increased from 1420.2 MCM in 2015 to 1444.8 MCM in 2050, which indicates an insignificant change over the time. Agricultural water demand in Northern borders is expected to be satisfied by TWW. The largest extraction of GW for agriculture is needed for Riyadh, which can be reduced from 2858.5 MCM in 2015 to 2162.1 MCM in 2050. This reduction is needed to be supplemented by TWW. Insignificant increase in GW extraction is noted for Al-Baha from 2015 through 2035 (from 57.6 MCM in 2015 to 58.5 MCM in 2035), while in 2040, 2045 and 2050 this extraction may be decreased to 58.3, 57.6 and 56.5 MCM respectively. In Makkah, GW extraction for agriculture is likely to reduce to 42.3, 21.1, 9.9 and 4.2 MCM in 2035, 2040, 2045 and 2050 respectively. The projected demands of GW to agricultural sector in Saudi Arabia may be reduced from 10483 MCM in 2015 to 8753 MCM in 2050 (approximately 0.5% reduction per year). The total withdrawal of SW for agriculture is expected to reduce from 236.6 MCM in 2015 to 95.2 MCM in 2050, indicating a reduction of approximately 1.7% per year. The decrease of SW in agriculture can be explained by the increase of SW to satisfy domestic water demands. Reuse of TWW for agriculture shows increasing trends in all regions. Notably, agricultural water demands in the Northern borders can be fully satisfied from the TWW (6 MCM/year). Riyadh needs to reuse the largest amount of TWW (608.5 MCM in 2015 and 1304.9 MCM in 2050). The analysis shows that the TWW reuse in the country needs to be increased to 2074.4 MCM in 2015 and 3945.8 MCM in 2050, indicating an annual increase of approximately 2.6% per year from 2015's need. In 2015, about 70.3% of TWW is needed to be reused in three regions (Riyadh: 29.3%; Makkah: 25.9%; Eastern region: 15.1%). It is to be noted that GW and SW contributions to agriculture may be reduced from 82% to 68.4% and 1.8% to 0.7%, respectively, from 2015 to 2050.

Table 5.41: Source wise water needed for agricultural sectors in the regions of Saudi Arabia (MCM/year).

Year	Demand	Supply	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2858.5	193.9	630.4	1788.2	420.4	217.3	1058.5	504.1	57.6	0	1161.2	1420.2	172.7	10483
	SW			5				1.9			16.7			213	0	236.6
	TWW		608.5	538.1	144.6	77.8	313.6	110.8	40.5	60.9	25.7	6	34.8	78.8	34.3	2074.4
2020	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2788.5	150.4	612.2	1779.3	389.4	206.7	1054	496.8	58	0	1157.5	1422.7	168	10283.5
	SW			2.5				0.9			14.6			200.7	0	218.7
	TWW		678.5	584.1	162.8	86.7	344.6	122.4	45	68.2	27.5	6	38.5	88.6	39	2291.9
2025	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2170.6	110	592.3	1769.4	355.5	194.5	1049.2	488.5	58.3	0	1153.5	1425.7	162.8	10070.3
	SW			0.2				0.4			12.5			186.5	0	199.6
	TWW		756.4	626.8	182.7	77.8	378.5	135.1	49.8	76.5	29.3	6	42.5	99.8	44.2	2505.4
2030	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2623.6	74.3	568.7	1758.3	318.1	180.8	1043.7	479.3	58.5	0	1149.1	1424.7	156.7	9835.8
	SW			0.9				0.2			10.4			171.2	0	182.7
	TWW		843.4	661.8	206.3	107.7	415.9	149.1	55.3	85.7	31.1	6	46.9	116.1	50.3	2775.6
2035	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2526.6	42.3	543.3	1746.2	277.1	165.3	1037.7	469	58.5	0	1144.2	1432.2	149.8	9592.2
	SW			3.1				0			8.2		153.4	153.4	0	164.7
	TWW		940.4	691.5	231.7	119.8	456.9	164.7	61.3	96	33.3	6	126.4	126.4	57.2	3037
2040	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2418.6	21.1	513.4	1732.5	232.3	148.2	1031	457.4	58.3	0	1138.8	1436	141.9	9329.5
	SW			5.8				0			6.2			133.7	0	145.7
	TWW		1048.4	710.1	261.6	133.5	501.7	181.8	68	107.6	35.5	6	57.2	142.3	65.1	3318.8
2045	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2299	9.9	480.5	1716.6	186.9	129.3	1023.5	444.5	57.6	0	1132.8	1446	133	9059.6
	SW			5.3				0.1			4.5			106.1	0	116
	TWW		1168	721.8	294.5	149.4	547.1	200.7	75.5	120.5	37.9	6	63.2	159.9	74	3618.5
2050	Demand		3467	737	775	1866	734	330	1099	565	100	6	1196	1712	207	12794
	GW		2162.1	4.2	443.5	1699.5	141.3	106.6	1015.3	429.9	56.5	0	1126.4	1444.8	122.9	8753
	SW			3.5				1.8			3.2			86.7	0	95.2
	TWW		1304.9	729.3	331.5	166.5	592.7	221.6	83.7	135.1	40.4	6	69.6	180.4	84.1	3945.8

GW: Groundwater; SW: Surface water; TWW: Treated wastewater.

5.15.1.3 Industrial Water Demands

Table 5.42 shows the industrial water demands while GW is the only source to satisfy the demands in different regions. Water demands in the industrial sectors show increasing trend. The maximum demand for industrial water is noted for Riyadh, which is likely to increase from 328.5 MCM in 2015 to 2078.7 MCM in 2050. The minimum water demand in industrial sector is noted for the Northern borders, which may increase from 4.1 MCM in 2015 to 25.7 MCM in 2050. In 2015, total water demand in industrial sector has been estimated to be 992.6 MCM, while in 2050 this demand may increase to approximately 6428.3 MCM. Riyadh, Makkah and Eastern region need approximately 80.5-81.3% of the total industrial water demands (33-32.7% in Riyadh, 20-20.4% in Makkah and 27.5-28.2% in Eastern region).

Table 5.42: Needs of GW for industrial purposes in the regions of Saudi Arabia (MCM/year).

Year	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	328.5	200.5	72.4	29.3	275.6	22.3	9.8	11.1	7	4.1	13.9	11.1	7	992.6
2020	429.4	262	94.6	38.2	360.2	29.1	12.6	14.5	9.1	5.5	18.2	14.5	9.1	1297
2025	561.1	342.4	119.1	50	470.7	38.1	16.7	19	11.9	7.2	23.8	19	11.9	1690.9
2030	733.4	447.5	161.6	64.5	615.3	49.8	21.7	24.8	15.5	9.3	31.1	24.8	15.5	2214.8
2035	920	566.1	204	81.1	798	66.7	32.5	34.9	22.5	11.5	39.9	36.9	22.9	2837
2040	1229	768	276.8	104.5	1043	87.2	42.5	45.6	29.5	15.1	52.2	48.4	30	3771.8
2045	1606.2	1003.8	361.8	141.8	1363.3	114.1	55.6	59.7	38.5	19.7	68.1	60.9	39.2	4932.7
2050	2078.7	1311.9	472.9	185.3	1781.7	149.1	72.7	77.9	50.3	25.7	89.1	81.8	51.2	6428.3

5.15.2 Source Wise Predicted Water Demands

Table 5.43 shows the predicted quantities of water to be supplied from various sources in different regions of Saudi Arabia for the period of 2015 to 2050. Extraction of GW is expected to increase in all regions with a rate of 0.03-0.9% per year. The highest extraction of GW is noted for Riyadh (3286.3 MCM in 2015 to 4345.4 MCM in 2050), while the lowest extraction is predicted for the Northern borders (31.6 MCM in 2015 to 88.8 MCM in 2050). The total predicted quantity of water to be extracted from GW sources in the country has been estimated to be 11933 MCM in 2015, which is expected to increase to 15766 MCM by 2050 (approximately 32.1% increase). The total supply of SW in the country is predicted to be approximately 444.3 MCM/year. In 2015, total supply of DW is predicted to be 1959.4 MCM, in which approximately 662.2, 554.1 and 341.3 MCM is attributed by Riyadh, Makkah and Eastern region respectively. By 2050, DW supply is needed to be increased to 4494.8 MCM (approximately 2.3 times to the supply of 2015), from which 1553.6, 1262.9 and 758.4 MCM have been predicted for Riyadh, Makkah and Eastern region respectively. The predicted quantity of TWW was assumed to be equal to the generated wastewater (e.g., full treatment), which needs to be ensured through collecting the total domestic wastewater, treating and recycling for agricultural purposes. Total TWW reuse has been estimated to be 2074.4 MCM in 2015 and 3945.8 MCM in 2050.

It is to be noted that industrial water demands in different regions of the country from 2015-2050 need to be satisfied by GW. Further, domestic water demands in Hail, Northern borders and Al-Jouf regions are needed to be satisfied by GW. Further, most of the agricultural water demands are needed to be satisfied by GW, making the GW sources vulnerable. Increased extraction of GW is likely to compromise the objective of GW conservation. To maximize GW conservation, several possibilities including: augmentation of SW sources, increase of DW supply and development of new sources (e.g., rain water harvesting) can be investigated in future.

Table 5.43: Predicted water demands from different sources in the regions of Saudi Arabia (MCM/year).

Year	Source	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	GW	3286.3	477.4	727.2	1830.2	747.1	252	1119	525.1	64.6	31.6	1218.7	1432	222.2	11933
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	662.3	554.1	163.1	84.6	341.3	82.4		66.3				5.3		1959.4
	TWW	608.5	538.1	144.6	77.8	313.6	110.8	40.5	60.9	25.7	6	34.8	78.8	34.3	2074.4
2020	GW	3328.6	501.9	733.9	1831.6	805.9	249.9	1123.7	522.4	67.1	36.4	1223.8	1437.9	225.6	12089
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	738.4	611.9	180.8	94.4	374.9	94.2		74.3				5.3		2174.2
	TWW	678.5	584.1	162.8	86.7	344.6	122.4	45	68.2	27.5	6	38.5	88.6	39	2291.9
2025	GW	3395.1	549.5	742.1	1835.1	880.4	248.7	1128.2	519.9	70.4	42	1230.5	1445.3	229.8	12317
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	823.2	675.3	204.4	105.2	419.5	107.6		83.3				5.1		2423.6
	TWW	756.4	626.8	182.7	77.8	378.5	135.1	49.8	76.5	29.3	6	42.5	99.8	44.2	2505.4
2030	GW	3494.7	631.8	764	1840	976.8	248.9	1134.6	518.1	74.5	48.5	1238.9	1450.2	234.9	12656
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	917.8	743.5	224.5	115.4	477.1	122.7		93.3				5.5		2699.8
	TWW	843.4	661.8	206.3	107.7	415.9	149.1	55.3	85.7	31.1	6	46.9	116.1	50.3	2775.6
2035	GW	3601.1	729	786.2	1847	1103.1	253	1146.9	519.5	82	55.7	1248.9	1469.9	244	13086
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	1030.1	848.3	259.1	131.9	543.9	139.5		104.5				5.3		3062.6
	TWW	940.4	691.5	231.7	119.8	456.9	164.7	61.3	96	33.3	6	126.4	126.4	57.2	3037
2040	GW	3814	874	832.4	1859	1287	259.1	1159	520.5	89.6	64.9	1263	1485	253	13759
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	1145.9	959.3	285.2	149.5	617.1	158.1		117.2				5.4		3437.7
	TWW	1048.4	710.1	261.6	133.5	501.7	181.8	68	107.6	35.5	6	57.2	142.3	65.1	3318.8
2045	GW	4053	1048	882.2	1883	1552	270.1	1174	523.8	99.1	75.7	1280	1508	264.4	14613
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	1314.7	1115.8	328.6	162.6	688.3	178.7		131.2				5.4		3925.3
	TWW	1168	721.8	294.5	149.4	547.1	200.7	75.5	120.5	37.9	6	63.2	159.9	74	3618.5
2050	GW	4345.4	1319.1	948.9	1911.9	1923	286.1	1192.7	529.8	111.5	88.8	1302.7	1527.5	279	15766
	SW		43.8				45.7			48.9			305.6	0.3	444.3
	DW	1553.6	1262.9	382.4	181.3	758.4	203.1		147				6.1		4494.8
	TWW	1304.9	729.3	331.5	166.5	592.7	221.6	83.7	135.1	40.4	6	69.6	180.4	84.1	3945.8

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater.

5.15.3 Balancing Model Predictions and Supplies

The model predictions and source wise current supplies of water are presented in Appendix. In 2015, extraction rates of GW are within the current limits of GW extraction in all regions, meaning that the priority to maximize GW conservation was achieved. However, model predictions do not comply with the GW extraction rates in some regions in 2050. In 2050, there are additional needs of approximately 408.1, 892.9, 11.3, 57.3 and 0.6 MCM of GW in Makkah, Eastern region, Al-Baha, Northern borders and Najran region respectively. Extraction of adequate GW is likely to be a concern in these regions. So, the main issue is how to achieve a balance among the demands and supplies in these regions in 2050. Among these regions (Makkah, Eastern region, Al-Baha, Northern borders and Najran), SW is in practice in Makkah, Al-Baha and Najran region, which is likely to be fully used. Two regions (Makkah and Eastern region) also get DW, while Al-Baha, Northern borders and Najran do not have any DW. Augmentation of SW sources and/or introduction of DW to these three regions (Al-Baha, Northern borders and Najran) might be essential in future. Alternatively, agricultural water demands might be reduced accordingly. A comprehensive balance analysis is warranted for these regions.

The balance analysis for DW indicates significant differences between the demands and supplies in almost all regions. The demands of DW are higher than the supplies in almost all regions. There is a serious need to increase DW in most of the regions (Appendix). DW can satisfy the demands for the period of 2015 – 2020 in Makkah and 2015-2045 in Jazan. In 2015, there is a need to increase DW by 483.4 MCM, while in 2050; there is a need to increase DW by 3018.8 MCM. Further, domestic wastewater needs to be fully treated and recycled while such initiative can be an important supplement to the agricultural water supplies. At present, scope of reusing the domestic wastewater in full is limited. There is a need of serious initiative for reusing the domestic wastewater in full. Further details on the balance analysis for different sources are available in Appendix.

5.15.4 Source Wise Costs of Supplying Predicted Water

Table 5.44 shows the source wise costs for supplying predicted water in different regions from 2015 to 2050. The cost of using GW is likely to increase with time. In 2015, the maximum (in Riyadh region) and minimum (in Northern borders region) costs for supplying GW is expected be 6038.6 and 58.1 million SR respectively, which is likely to be 7984.5 and 163.1 million SR in 2050 respectively. The total cost for supplying GW has been estimated to be 21.9 billion SR in 2015, which is forecasted to be 29 billion SR in 2050, indicating an increase of approximately 0.9 % per year. From 2015-2050, the cost for using SW ranges from 0.4 million SR/year in Najran to 561.4 million SR/year in Jazan. Total cost of using SW is approximately 816.4 million SR per year. The cost for using DW in 2015 may range from 36.8 million SR in Jazan to 4569.8 million SR in Riyadh. In 2050, these costs are predicted to be 42 and 10719.8 million SR in Jazan and Riyadh respectively. The total cost for supplying DW in the country has been estimated to be 13.5 billion SR in 2015, in which about 33.8, 28.3 and 17.4 % is noted for Riyadh, Makkah and Eastern region. In 2050, the total cost of DW supply may be 31 billion SR (which is approximately 2.3 folds to the cost of 2015), in which about 34.6, 28.1 and 16.9 % is expected to be for Riyadh, Makkah and Eastern region respectively. In 2015, the cost for reusing TWW is predicted to be in the range of 32.3 million SR in Northern borders to 3263.3 million SR in Riyadh. In 2050, these costs are predicted to be 32.3 and 6997.5 million SR in Northern borders and Riyadh respectively. Between 2015 and 2050, the total cost for reusing TWW may increase at the rate of approximately 2.6% per year (from 11.1 billion SR in 2015 to 21.2 billion SR in 2050). The total cost of supplying water from all sources has been estimated to be 47.4 billion SR in 2015, while in 2050, this cost is predicted to be 82 billion SR, indicating an increase of approximately 2.1% per year.

Noteworthy, in 2015, 10 of 13 regions show that the total costs for supplying GW were higher than SW, DW and TWW. In Aseer, total costs of reusing TWW is higher, while in Makkah and Eastern region, total costs of DW were higher. In 2050, total costs of DW were higher in six regions: Riyadh, Makkah, Madinah, Eastern region, Aseer and Tabouk. At this time, seven regions (Qaseem, Hail, Al-Baha, Northern borders, Al-Jouf, Jazan and Najran) will have the higher total costs for GW.

Table 5.44: Costs of supplying predicted quantities of water from different sources in the regions of Saudi Arabia (million SR/year).

Year	Source	Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	GW	6038.6	877.1	1336.1	3363.0	1372.9	463.1	2056.1	964.9	118.9	58.1	2239.5	2631.4	408.4	21928.1
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	4569.8	3823.1	1125.4	583.9	2355.0	568.5		457.5				36.8		13519.9
	TWW	3263.3	2885.6	775.5	417.4	1681.5	594.0	217.1	326.6	138.0	32.3	186.8	422.6	183.8	11124.4
	Total	13871.6	7666.5	3237.0	4363.9	5409.4	1709.6	2273.3	1749.0	346.5	90.4	2425.9	3652.1	592.9	47388.0
2020	GW	6116.3	922.1	1348.5	3365.6	1480.9	459.4	2064.8	960.0	123.4	66.8	2248.9	2642.3	414.4	22213.1
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	5095.1	4222.1	1247.6	651.4	2586.8	649.9		512.6				36.8		15002.3
	TWW	3638.6	3132.4	873.0	465.0	1848.0	656.3	241.5	365.6	147.4	32.3	206.6	475.1	209.3	12291.0
	Total	14849.6	8357.3	3469.1	4482.0	5915.6	1849.5	2306.3	1838.3	360.8	99.0	2455.1	3715.5	624.4	50322.4
2025	GW	6238.5	1009.9	1363.5	3372.0	1617.8	457.1	2073.0	955.5	129.4	77.3	2260.9	2655.8	422.3	22632.8
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	5680.1	4659.8	1410.4	726.0	2894.6	742.5		574.9				35.3		16723.5
	TWW	4056.4	3361.1	979.9	417.4	2029.9	724.5	267.0	410.3	157.1	32.3	228.0	535.1	237.0	13435.9
	Total	15974.6	9111.0	3753.8	4515.0	6541.9	2007.8	2340.0	1940.3	376.5	109.5	2488.9	3787.5	660.0	53606.6
2030	GW	6421.5	1161.0	1404.0	3381.0	1794.8	457.5	2085.0	952.1	136.9	89.3	2276.6	2664.8	431.6	23256.0
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	6333.0	5130.0	1549.1	796.1	3292.1	846.8		643.9				37.9		18628.9
	TWW	4522.9	3549.0	1106.3	577.5	2230.1	799.5	296.6	459.8	166.9	32.3	251.6	622.5	269.6	14884.5
	Total	17277.0	9920.6	4059.0	4754.6	7317.0	2187.4	2381.3	2055.4	393.4	121.1	2527.9	3886.9	702.0	57583.5
2035	GW	6616.9	1339.5	1444.5	3393.8	2026.9	465.0	2107.5	954.8	150.8	102.4	2295.0	2701.1	448.5	24046.5
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	7107.8	5853.4	1787.6	910.1	3753.0	962.6		721.1				36.8		21132.4
	TWW	5043.0	3708.0	1242.4	642.4	2450.3	883.1	328.9	514.9	178.5	32.3	678.0	678.0	306.8	16686.4
	Total	18767.6	10981.5	4474.9	4946.3	8230.1	2394.8	2436.0	2190.4	419.3	134.6	2972.6	3976.9	755.6	62680.5
2040	GW	7008.4	1606.1	1529.6	3415.9	2364.8	476.3	2129.6	956.3	164.6	119.3	2320.9	2728.9	465.0	25285.5
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	7906.9	6619.1	1968.0	1031.6	4258.1	1090.9		808.5				37.1		23720.3
	TWW	5622.0	3807.8	1402.9	715.9	2690.3	975.0	364.5	577.1	190.5	32.3	306.8	763.1	349.1	17797.1
	Total	20536.9	12113.6	4900.1	5163.4	9313.1	2625.8	2494.5	2342.3	444.8	151.5	2627.6	4090.5	814.5	67618.5
2045	GW	7447.5	1925.6	1621.1	3460.1	2851.9	496.1	2157.4	962.6	182.3	139.1	2352.0	2770.9	486.0	26852.6
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	9071.3	7699.1	2267.3	1122.0	4749.4	1233.0		905.3				37.1		27084.4
	TWW	6263.3	3870.8	1579.1	801.0	2934.0	1076.3	405.0	646.1	203.3	32.3	339.0	857.6	396.8	19404.4
	Total	22782.4	13575.8	5467.5	5383.1	10534.9	2889.8	2562.0	2514.0	475.1	171.4	2691.0	4227.4	883.1	74157.4
2050	GW	7984.5	2424.0	1743.8	3513.0	3533.6	525.8	2191.5	973.5	204.8	163.1	2393.6	2806.9	512.6	28970.6
	SW		80.6				84.0			90.0			561.4	0.4	816.4
	DW	10719.8	8713.9	2638.5	1251.0	5233.1	1401.4		1014.4				42.0		31014.0
	TWW	6997.5	3910.9	1777.5	892.9	3178.5	1188.4	448.9	724.5	216.8	32.3	373.1	967.5	451.1	21159.8
	Total	25702.1	15129.4	6159.8	5656.9	11944.9	3199.5	2640.4	2712.4	511.5	195.4	2767.1	4377.8	964.1	81961.1

GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Saudi Arabia is a water deficit country with low rainfall and limited water resources. Water scarcity has become an issue in Saudi Arabia, which has made it difficult for the country to keep pace with water demands. The water consumption patterns and resources indicate that Saudi Arabia needs to manage water resources more efficiently. The difficulty associated with water resources management is to provide a balance between water demands and available water resources. To achieve sustainability in water resources, effective management of water resources needs to be followed. Optimal supplies of water from different resources are necessary to satisfy water demands in the domestic, agricultural and industrial sectors. In this study, a multi-objective GP model has been developed and applied for water distributions from multiple resources to multiple users in different regions of Saudi Arabia. The model was applied for the period of 2015 through 2050. Uncertainties in water demands and supplies were incorporated through generating 100 random realizations of sector wise water demands and source wise water supplies. The GP model was trained to achieve a set of goals through satisfying a set of constraints. The model identified the combinations of source wise supplies for satisfying sector wise demands for the period of 2015 – 2050.

The domestic water demands were estimated to increase from 2625.2 MCM in 2015 to 5429.2 MCM in 2050, which may be satisfied through the combinations of GW, SW and DW in most of the regions. Five regions (Makkah, Eastern region, Al-Baha, Northern borders and Najran region) may have difficulties in extracting additional GW (assuming that the current withdrawal rates of GW are in effect). Both DW and SW may need significant augmentation. Most of untreated and treated domestic wastewater are wasted in the country, while reuse of TWW for agriculture can provide significant support toward achieving essential food sustainability. However, regional wise comprehensive understanding on water demands and supplies are needed to better plan and manage water resources. This study recommends the following research in future:

- Better understanding of seasonal variability in water demands in the domestic, agricultural and industrial sectors.
- Effects of climate change on water demands in various sectors.
- Water loss through leakage in the distribution systems.
- Wastewater generation, collection, treatment and recycling for agriculture.
- Possibility of rainwater harvesting and storage of surface runoff.
- Effects of water conservation measures on water consumption.

APPENDIX

Appendix: Balancing source wise predicted water demands and current supplies in the regions of Saudi Arabia (MCM/year).

Year	Source		Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2015	GW	PD	3286.3	477.4	727.2	1830.2	747.1	252	1119	525.1	64.6	31.6	1218.7	1432	222.2	11933
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	662.3	554.1	163.1	84.6	341.3	82.4		66.3				5.3		1959.4
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	608.5	538.1	144.6	77.8	313.6	110.8	40.5	60.9	25.7	6	34.8	78.8	34.3	2074.4
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5
2020	GW	PD	3328.6	501.9	733.9	1831.6	805.9	249.9	1123.7	522.4	67.1	36.4	1223.8	1437.9	225.6	12089
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	738.4	611.9	180.8	94.4	374.9	94.2		74.3				5.3		2174.2
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	678.5	584.1	162.8	86.7	344.6	122.4	45	68.2	27.5	6	38.5	88.6	39	2291.9
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5
2025	GW	PD	3395.1	549.5	742.1	1835.1	880.4	248.7	1128.2	519.9	70.4	42	1230.5	1445.3	229.8	12317
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	823.2	675.3	204.4	105.2	419.5	107.6		83.3				5.1		2423.6
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	756.4	626.8	182.7	77.8	378.5	135.1	49.8	76.5	29.3	6	42.5	99.8	44.2	2505.4
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5
2030	GW	PD	3494.7	631.8	764	1840	976.8	248.9	1134.6	518.1	74.5	48.5	1238.9	1450.2	234.9	12656
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	917.8	743.5	224.5	115.4	477.1	122.7		93.3				5.5		2699.8
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	843.4	661.8	206.3	107.7	415.9	149.1	55.3	85.7	31.1	6	46.9	116.1	50.3	2775.6
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5

GW [a] Capacities of dams that constructed for drinking and irrigation purposes; [b] the existing capacities of sewage plants; GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater; PD: Predicted demand; CS: Current supply.

Appendix: (Continued).

Year	Source		Riyadh	Makkah	Madinah	Qaseem	Eastern region	Aseer	Hail	Tabouk	Al-Baha	Northern borders	Al-Jouf	Jazan	Najran	Total
2035	GW	PD	3601.1	729	786.2	1847	1103.1	253	1146.9	519.5	82	55.7	1248.9	1469.9	244	13086
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	1030.1	848.3	259.1	131.9	543.9	139.5		104.5				5.3		3062.6
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	940.4	691.5	231.7	119.8	456.9	164.7	61.3	96	33.3	6	126.4	126.4	57.2	3037
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5
2040	GW	PD	3814	874	832.4	1859	1287	259.1	1159	520.5	89.6	64.9	1263	1485	253	13759
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	1145.9	959.3	285.2	149.5	617.1	158.1		117.2				5.4		3437.7
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	1048.4	710.1	261.6	133.5	501.7	181.8	68	107.6	35.5	6	57.2	142.3	65.1	3318.8
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5
2045	GW	PD	4053	1048	882.2	1883	1552	270.1	1174	523.8	99.1	75.7	1280	1508	264.4	14613
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	1314.7	1115.8	328.6	162.6	688.3	178.7		131.2				5.4		3925.3
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	1168	721.8	294.5	149.4	547.1	200.7	75.5	120.5	37.9	6	63.2	159.9	74	3618.5
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5
2050	GW	PD	4345.4	1319.1	948.9	1911.9	1923	286.1	1192.7	529.8	111.5	88.8	1302.7	1527.5	279	15766
		CS	4368.9	911.0	979.0	2190.7	1030.2	372.3	1300.5	729.8	100.2	31.5	1425.6	1689.7	278.4	15407.8
	SW	PD		43.8				45.7			48.9			305.6	0.3	444.3
		[a]CS		43.8				45.7			48.9			305.6	0.3	444.3
	DW	PD	1553.6	1262.9	382.4	181.3	758.4	203.1		147				6.1		4494.8
		CS	338.0	613.0	131.0	8.0	316.0	54.0		10.0				6.0		1476
	TWW	PD	1304.9	729.3	331.5	166.5	592.7	221.6	83.7	135.1	40.4	6	69.6	180.4	84.1	3945.8
		[b]CS	345.8	357.0	109.5	52.6	651.7	133.8	4.4	21.9		8.8	14.6	7.5	21.9	1729.5

[a] Capacities of dams that constructed for drinking and irrigation purposes; [b] the existing capacities of sewage plants; GW: Groundwater; SW: Surface water; DW: Desalinated water; TWW: Treated wastewater; PD: Predicted demand; CS: Current supply.

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